3

Communication & Synchronization

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Overview

Synchronization methods

Shared memory based synchronization

• Semaphores	☞ C, POSIX — Dijkstra
• Conditional critical regions	☞ Edison (experimental)
• Monitors	☞ Modula-1, Mesa — Dijkstra, Hoare, …
• Mutexes & conditional variables	☞ POSIX
• Synchronized methods	☞ Java, C#, …
• Protected objects	☞ Ada
• Atomic blocks	☞ Chapel, X10

Message based synchronization

• Asynchronous messages	☞ e.g. POSIX, …
• Synchronous messages	☞ e.g. Ada, CHILL, Occam2, …
• Remote invocation, remote procedure call	☞ e.g. Ada, …

Motivation

Side effects

Operations have side effects which are visible …

either

☞ … **locally only**

(and protected by runtime-, os-, or hardware-mechanisms)

or

☞ … **outside the current process**

☞ If side effects transcend the local process then all forms of access need to be synchronized.

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
                    i++;                    if i > n {i=0;}
                    {in one thread}         {in another thread}
```

What's the worst that can happen?

Communication & Synchronization

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
                    i++;                    if i > n {i=0;}
                    {in one thread}         {in another thread}
```

☞ Handling a 64-bit integer on a 8- or 16-bit controller will not be atomic

… yet perhaps it is an 8-bit integer.

☞ Unaligned manipulations on the main memory will usually not be atomic

… yet perhaps it is a aligned.

☞ Broken down to a load-operate-store cycle, the operations will usually not be atomic

… yet perhaps the processor supplies atomic operations for the actual case.

☞ Many schedulers interrupt threads irrespective of shared data operations

… yet perhaps this scheduler is aware of the shared data.

☞ Local caches might not be coherent

… yet perhaps they are.

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}

                    i++;                    if i > n {i=0;}

                    {in one thread}         {in another thread}
```

☞ Handling a 64-bit integer on a 8- or 16-bit controller will not be atomic

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… yet perhaps it is a aligned.

☞ Broken down to a load-operate-store cycle, the operations will usually not be atomic

… yet perhaps the processor supplies atomic operations for the actual case.

☞ Many schedulers interrupt threads irrespective of shared data operations

… yet perhaps this scheduler is aware of the shared data.

☞ Local caches might not be coherent

… yet perhaps they are.

Even if all assumptions hold:

How to expand this code?

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}

                    i++;                    if i > n {i=0;}

                    {in one thread}         {in another thread}
```

☞ The chances that such programming errors turn out are usually small and some implicit by chance synchronization in the rest of the system might prevent them at all.

(Many effects stemming from asynchronous memory accesses are interpreted as (hardware) 'glitches', since they are usually rare, yet often disastrous.)

☞ On assembler level on very simple CPU architectures: synchronization by employing knowledge about the atomicity of CPU-operations and interrupt structures is nevertheless possible and utilized in practice.

In anything higher than assembler level on single core, predictable μ-controllers:

☞ Measures for synchronization are required!

Towards synchronization

Condition synchronization by flags

Assumption: word-access atomicity:

i.e. assigning two values (not wider than the size of a ‘word’) to an aligned memory cell concurrently:

```
x := 0   |   x := 500
```

will result in *either* `x = 0` *or* `x = 500` – and no other value is ever observable

Towards synchronization

Condition synchronization by flags

Assuming further that there is a shared memory area between two processes:

- A set of processes agree on a (word-size) atomic variable operating as a flag to indicate synchronization conditions:

Condition synchronization by flags

```
var Flag : boolean := false;
```

```
process P1;                              process P2;
  statement X;                             statement A;
  repeat until Flag;                       Flag := true;
  statement Y;                             statement B;
end P1;                                  end P2;
```

Sequence of operations: $A \rightharpoonup B; [X \mid A] \rightharpoonup Y; [X, Y \mid B]$

Towards synchronization

Condition synchronization by flags

Assuming further that there is a shared memory area between two processes:

- A set of processes agree on a (word-size) atomic variable operating as a flag to indicate synchronization conditions:

Memory flag method is ok for simple condition synchronization, but …

☞ … is not suitable for general mutual exclusion in critical sections!

☞ … busy-waiting is required to poll the synchronization condition!

☞ More powerful synchronization operations are required for critical sections

Basic synchronization

by Semaphores

Basic definition (Dijkstra 1968)

Assuming the following three conditions on a shared memory cell between processes:

- a set of processes agree on a variable **S** operating as a flag to indicate synchronization conditions
- an atomic operation **P** on S — for 'passeren' (Dutch for 'pass'):

  P(S): `[as soon as S > 0 then S := S - 1]` ☞ this is a potentially delaying operation

  aka: 'Wait', 'Suspend_Until_True', 'sem_wait', …
- an atomic operation **V** on S — for 'vrygeven' (Dutch for 'to release'):

  V(S): `[S := S + 1]`

  aka 'Signal', 'Set-True', 'sem_post', …

☞ *then* the variable **S** is called a **Semaphore**.

Towards synchronization

Condition synchronization by semaphores

```
var sync : semaphore := 0;
```

```
process P1;
  statement X;
  wait (sync)
  statement Y;
end P1;
```

```
process P2;
  statement A;
  signal (sync);
  statement B;
end P2;
```

Sequence of operations: $A \rightharpoonup B; [X \mid A] \rightharpoonup Y; [X, Y \mid B]$

Towards synchronization

Mutual exclusion by semaphores

```
var mutex : semaphore := 1;
```

```
process P1;                     process P2;
  statement X;                    statement A;
  wait (mutex);                   wait (mutex);
    statement Y;                    statement B;
  signal (mutex);                 signal (mutex);
  statement Z;                    statement C;
end P1;                         end P2;
```

Sequence of operations:

$A \rightharpoonup B \rightharpoonup C; X \rightharpoonup Y \rightharpoonup Z; [X,Z \mid A,B,C]; [A,C \mid X,Y,Z]; \neg[B \mid Y]$

Towards synchronization

Semaphores in Ada

```
package Ada.Synchronous_Task_Control is
  type Suspension_Object is limited private;
  procedure Set_True          (S : in out Suspension_Object);
  procedure Set_False         (S : in out Suspension_Object);
  function  Current_State     (S :        Suspension_Object) return Boolean;
  procedure Suspend_Until_True (S : in out Suspension_Object);
private
  … ------ not specified by the language
end Ada.Synchronous_Task_Control;
```

☞ This is "queueless" and can translate into a single machine instruction.

only one task can be blocked at `Suspend_Until_True`!
(`Program_Error` will be raised with a second task trying to suspend itself)

☞ no queues! ☞ minimal run-time overhead

Towards synchronization

Semaphores in Ada

```
package Ada.Synchronous_Task_Control is
  type Suspension_Object is limited private;
  procedure Set_True           (S : in out Suspension_Object);
  procedure Set_False          (S : in out Suspension_Object);
  function  Current_State      (S :        Suspension_Object) return Boolean;
  procedure Suspend_Until_True (S : in out Suspension_Object);
private
  … ------ not specified by the language
end Ada.Synchronous_Task_Control;
```

☞ for special cases only … otherwise:

medieval

only one task can be blocked at Suspend_Until_True!
(Program_Error will be raised with a second task trying to suspend itself)

☞ no queues! ☞ minimal run-time overhead

Towards synchronization

Malicious use of "queueless semaphores"

```
with Ada.Synchronous_Task_Control; use Ada.Synchronous_Task_Control;
X : Suspension_Object;
```

```
task B;
task body B is
begin
  …
  Suspend_Until_True (X);
  …
  …
end B;
```

```
task A;
task body A is
begin
  …
  Suspend_Until_True (X);
  …
  …
end A;
```

☞ Could raise a `Program_Error` as multiple tasks potentially suspend on the same semaphore (occurs only with high efficiency semaphores which do not provide process queues)

Towards synchronization

Malicious use of "queueless semaphores"

```
with Ada.Synchronous_Task_Control; use Ada.Synchronous_Task_Control;
X, Y : Suspension_Object;
```

```
task B;
task body B is
begin
  …
  Suspend_Until_True (Y);
  Set_True (X);
  …
end B;
```

```
task A;
task body A is
begin
  …
  Suspend_Until_True (X);
  Set_True (Y);
  …
end A;
```

☞ Will result in a deadlock (assuming no other `Set_True` calls)

Towards synchronization

Malicious use of "queueless semaphores"

```
with Ada.Synchronous_Task_Control; use Ada.Synchronous_Task_Control;
X, Y : Suspension_Object;
```

```
task B;
task body B is
begin
  …
  Suspend_Until_True (Y);
  Suspend_Until_True (X);
  …
end B;
```

```
task A;
task body A is
begin
  …
  Suspend_Until_True (X);
  Suspend_Until_True (Y);
  …
end A;
```

☞ Will potentially result in a deadlock (with general semaphores) or a `Program_Error` in Ada.

Towards synchronization

Semaphores in POSIX

pshared is actually a Boolean indicating whether the semaphore is to be shared between processes

```
int sem_init       (sem_t *sem_location, int pshared, unsigned int value);
int sem_destroy    (sem_t *sem_location);
int sem_wait       (sem_t *sem_location);
int sem_trywait    (sem_t *sem_location);
int sem_timedwait (sem_t *sem_location, const struct timespec *abstime);
int sem_post       (sem_t *sem_location);
int sem_getvalue  (sem_t *sem_location, int *value);
```

*value indicates the number of waiting processes as a negative integer in case the semaphore value is zero

Semaphores in POSIX

```
sem_t mutex, cond[2];
typedef emun {low, high} priority_t;
int waiting;
int busy;

void allocate (priority_t P)
{
  sem_wait (&mutex);
  if (busy) {
    sem_post (&mutex);
    sem_wait (&cond[P]);
  }
  busy = 1;
  sem_post (&mutex);
}
```

```
void deallocate (priority_t P)
{
  sem_wait (&mutex);
  busy = 0;
  sem_getvalue (&cond[high], &waiting);
  if (waiting < 0) {
    sem_post (&cond[high]);
  }
  else {
    sem_getvalue (&cond[low], &waiting);
    if (waiting < 0) {
      sem_post (&cond[low]);
    }
    else {
      sem_post (&mutex);
} } }
```

Deadlock?

Livelock?

Mutual exclusion?

Towards synchronization

Semaphores in Java *(since 2004)*

```
Semaphore (int permits, boolean fair)
          void    acquire                 ()
          void    acquire                 (int permits)
          void    acquireUninterruptibly  (int permits)
          boolean tryAcquire              ()
          boolean tryAcquire              (int permits, long timeout, TimeUnit unit)

          int     availablePermits        ()
protected void    reducePermits           (int reduction)
          int     drainPermits            ()

          void    release                 ()
          void    release                 (int permits)

protected Collection <Thread> getQueuedThreads ()
          int     getQueueLength          ()
          boolean hasQueuedThreads        ()
          boolean isFair                  ()
          String  toString                ()
```

wait

check and manipulate

signal

administration

Review of semaphores

- Semaphores are **not bound to any resource or method or region**
  - ☞ Compiler has no idea what is supposed to be protected by a semaphore.
- Semaphores are **scattered all over the code**
  - ☞ Hard to read and highly error-prone.
  - ☞ Adding or deleting a single semaphore operation usually stalls a whole system.

☞ Semaphores are generally considered inadequate for non-trivial systems.

(all concurrent languages and environments offer efficient and higher-abstraction synchronization methods)

☞ Special (usually close-to-hardware) applications exist.

Distributed synchronization

Conditional Critical Regions

Basic idea:

- Critical regions are a *set of associated code sections in different processes,* which are guaranteed to be executed in **mutual exclusion**:
  - Shared data structures are grouped in named regions and are *tagged* as being private resources.
  - Processes are prohibited from entering a critical region, when another process is active in any *associated* critical region.

- **Condition synchronisation** is provided by *guards*:
  - When a process wishes to *enter* a critical region it evaluates the guard (under mutual exclusion). If the guard evaluates to false, the process is suspended / delayed.

- Generally, no access order can be assumed ☞ potential livelocks

Distributed synchronization

Conditional Critical Regions

```
buffer : buffer_t;
resource critial_buffer_region : buffer;
```

```
process producer;
  loop
    region critial_buffer_region
      when buffer.size < N do
        ------ place in buffer etc.
    end region;
  end loop;
end producer;
```

```
process consumer;
  loop
    region critial_buffer_region
      when buffer.size > 0 do
        ------ take from buffer etc.
    end region;
  end loop;
end consumer;
```

Distributed synchronization

Review of Conditional Critical Regions

- Well formed synchronization blocks and synchronization conditions.
- Code, data and synchronization primitives are associated (known to compiler and runtime).

- All guards need to be re-evaluated, when any conditional critical region is left:
  ☞ all involved processes are activated to test their guards
  ☞ there is no order in the re-evaluation phase ☞ potential livelocks

- Condition synchronisation inside the critical code sections
  requires to leave and re-enter a critical region.

- As with semaphores the conditional critical regions are distributed all over the code.
  ☞ on a larger scale: same problems as with semaphores.

(The language Edison (Per Brinch Hansen, 1981) uses conditional critical regions for synchronization in a multiprocessor environment (each process is associated with exactly one processor).)

Centralized synchronization

Monitors

(Modula-1, Mesa — Dijkstra, Hoare)

Basic idea:

- Collect all *operations and data-structures* shared in critical regions in one place, the monitor.
- Formulate all operations as *procedures or functions*.
- Prohibit access to data-structures, other than by the monitor-procedures and functions.
- Assure mutual exclusion of all monitor-procedures and functions.

Centralized synchronization

Monitors

```
monitor buffer;
  export append, take;
  var (* declare protected vars *)
  procedure append (I : integer);
    …
  procedure take (var I : integer);
    …
begin
  (* initialisation *)
end;
```

How to implement conditional synchronization?

Centralized synchronization

Monitors with condition synchronization

(Hoare '74)

Hoare-monitors:

- Condition variables are implemented by semaphores (`Wait` and `Signal`).
- Queues for tasks suspended on condition variables are realized.
- A suspended task releases its lock on the monitor, enabling another task to enter.

☞ More efficient evaluation of the guards:
the task leaving the monitor can evaluate all guards and the right tasks can be activated.

☞ Blocked tasks may be ordered and livelocks prevented.

Centralized synchronization

Monitors with condition synchronization

```
monitor buffer;

  export append, take;

  var BUF                          : array [ … ] of integer;
  top, base                        : 0..size-1;
  NumberInBuffer                   : integer;
  spaceavailable, itemavailable : condition;

  procedure append (I : integer);
  begin
    if NumberInBuffer = size then
      wait (spaceavailable);
    end if;
    BUF [top] := I;
    NumberInBuffer := NumberInBuffer + 1;
    top := (top + 1) mod size;
    signal (itemavailable)
  end append; …
```

Centralized synchronization

Monitors with condition synchronization

```
…
  procedure take (var I : integer);
  begin
    if NumberInBuffer = 0 then
      wait (itemavailable);
    end if;
    I := BUF[base];
    base := (base+1) mod size;
    NumberInBuffer := NumberInBuffer-1;
    signal (spaceavailable);
  end take;
begin (* initialisation *)
  NumberInBuffer := 0;
  top            := 0;
  base           := 0
end;
```

The signalling and the waiting process are both active in the monitor!

Centralized synchronization

Monitors with condition synchronization

Suggestions to overcome the multiple-tasks-in-monitor-problem:

- A `signal` is allowed only as the *last action* of a process before it leaves the monitor.
- A `signal` operation has the side-effect of executing a `return` *statement*.
- Hoare, Modula-1, POSIX:
  a `signal` operation which unblocks another process has the side-effect of *blocking* the current process; this process will only execute again once the monitor is unlocked again.
- A `signal` operation which unblocks a process does not block the caller,
  but the unblocked process must re-gain access to the monitor.

Centralized synchronization

Monitors in Modula-1

- `procedure wait (s, r):`
  delays the caller until condition variable `s` is true (`r` is the rank (or 'priority') of the caller).
- `procedure send (s):`
  If a process is waiting for the condition variable `s`, then the process at the top of the queue of the highest filled rank is activated (and the caller suspended).
- `function awaited (s) return integer:`
  check for waiting processes on `s`.

Centralized synchronization

Monitors in Modula-1

```
INTERFACE MODULE resource_control;
  DEFINE allocate, deallocate;
  VAR busy : BOOLEAN; free : SIGNAL;
  PROCEDURE allocate;
  BEGIN
    IF busy THEN WAIT (free) END;
    busy := TRUE;
  END;
  PROCEDURE deallocate;
  BEGIN
    busy := FALSE;
    SEND (free); ------ or: IF AWAITED (free) THEN SEND (free);
  END;
BEGIN
  busy := false;
END.
```

Centralized synchronization

Monitors in POSIX (‘C’)

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init    (      pthread_mutex_t     *mutex,
                           const pthread_mutexattr_t *attr);
int pthread_mutex_destroy (      pthread_mutex_t     *mutex);

int pthread_cond_init     (      pthread_cond_t      *cond,
                           const pthread_condattr_t  *attr);
int pthread_cond_destroy  (      pthread_cond_t      *cond);
…
```

Centralized synchronization

Monitors in POSIX ('C')

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init    (      pthread_mutex_t     *mutex,
                          const pthread_mutexattr_t *attr);
int pthread_mutex_destroy (      pthread_mutex_t     *mutex);

int pthread_cond_init     (      pthread_cond_t      *cond,
                          const pthread_condattr_t  *attr);
int pthread_cond_destroy  (      pthread_cond_t      *cond);
…
```

Attributes include:

- semantics for trying to lock a mutex which is locked already by the same thread
- sharing of mutexes and condition variables between processes
- priority ceiling
- clock used for timeouts
- …

Centralized synchronization

Monitors in POSIX ('C')

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init    (      pthread_mutex_t     *mutex,
                           const pthread_mutexattr_t *attr);
int pthread_mutex_destroy (      pthread_mutex_t     *mutex);

int pthread_cond_init     (      pthread_cond_t      *cond,
                           const pthread_condattr_t  *attr);
int pthread_cond_destroy  (      pthread_cond_t      *cond);
…
```

Undefined while locked

Undefined while threads are waiting

Centralized synchronization

Monitors in POSIX (‘C’)

(operators)

```
…

int pthread_mutex_lock      (      pthread_mutex_t *mutex);
int pthread_mutex_trylock   (      pthread_mutex_t *mutex);
int pthread_mutex_timedlock (      pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_mutex_unlock    (      pthread_mutex_t *mutex);

int pthread_cond_wait       (      pthread_cond_t  *cond,
                                   pthread_mutex_t *mutex);

int pthread_cond_timedwait  (      pthread_cond_t  *cond,
                                   pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_cond_signal     (      pthread_cond_t  *cond);
int pthread_cond_broadcast  (      pthread_cond_t  *cond);
```

unblocks *‘at least one’* thread

unblocks *all* threads

Communication & Synchronization

Centralized synchronization

Monitors in POSIX (‘C’)

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t *mutex);
int pthread_mutex_timedlock (       pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_mutex_unlock    (       pthread_mutex_t *mutex);

int pthread_cond_wait       (       pthread_cond_t  *cond,
                                    pthread_mutex_t *mutex);
int pthread_cond_timedwait  (       pthread_cond_t  *cond,
                                    pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_cond_signal     (       pthread_cond_t  *cond);
int pthread_cond_broadcast  (       pthread_cond_t  *cond);
```

undefined

if called ‘out of order’

i.e. mutex is not locked

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t *mutex);
int pthread_mutex_timedlock (       pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_mutex_unlock    (       pthread_mutex_t *mutex);

int pthread_cond_wait       (       pthread_cond_t  *cond,
                                    pthread_mutex_t *mutex);
int pthread_cond_timedwait  (       pthread_cond_t  *cond,
                                    pthread_mutex_t *mutex,
                             const struct timespec *abstime);

int pthread_cond_signal     (       pthread_cond_t  *cond);
int pthread_cond_broadcast  (       pthread_cond_t  *cond);
```

can be called
- any time
- anywhere
- multiple times

Communication & Synchronization

Centralized synchronization

```
#define BUFF_SIZE 10
typedef struct { pthread_mutex_t mutex;
                 pthread_cond_t buffer_not_full;
                 pthread_cond_t buffer_not_empty;
                 int count, first, last;
                 int buf [BUFF_SIZE];
               } buffer;
```

```
int append (int item, buffer *B) {
  PTHREAD_MUTEX_LOCK (&B->mutex);
  while (B->count == BUFF_SIZE) {
    PTHREAD_COND_WAIT (
                   &B->buffer_not_full,
                   &B->mutex);
  }
  PTHREAD_MUTEX_UNLOCK (&B->mutex);
  PTHREAD_COND_SIGNAL (
                 &B->buffer_not_empty);
  return 0;
}
```

```
int take (int *item, buffer *B) {
  PTHREAD_MUTEX_LOCK (&B->mutex);
  while (B->count == 0) {
    PTHREAD_COND_WAIT (
                   &B->buffer_not_empty,
                   &B->mutex);
  }
  PTHREAD_MUTEX_UNLOCK (&B->mutex);
  PTHREAD_COND_SIGNAL (
                   &B->buffer_not_full);
  return 0;
}
```

Communication & Synchronization

Centralized synchronization

```
#define BUFF_SIZE 10
typedef struct { pthread_mutex_t mutex;
                 pthread_cond_t buffer_not_full;
                 pthread_cond_t buffer_not_empty;
                 int count, first, last;
                 int buf [BUFF_SIZE];
               } buffer;

int append (int item, buffer *B) {
  PTHREAD_MUTEX_LOCK (&B->mutex);
  while (B->count == BUFF_SIZE) {
    PTHREAD_COND_WAIT (
                    &B->buffer_not_full,
                    &B->mutex);
  }
  PTHREAD_MUTEX_UNLOCK (&B->mutex);
  PTHREAD_COND_SIGNAL (
                  &B->buffer_not_empty);
  return 0;
}
```

need to be called
with a locked mutex

```
int take (int *item, buffer *B) {
  PTHREAD_MUTEX_LOCK (&B->mutex);
  while (B->count == 0) {
    PTHREAD_COND_WAIT (
                    &B->buffer_not_empty,
                    &B->mutex);
  }
  PTHREAD_MUTEX_UNLOCK (&B->mutex);
  PTHREAD_COND_SIGNAL (
                  &B->buffer_not_full);
  return 0;
}
```

better to be called
after unlocking all mutexes
(as it is itself potentially blocking)

Centralized synchronization

Monitors in C#

```
using System;
using System.Threading;
static long data_to_protect = 0;

static void Reader()
  { try {
      Monitor.Enter (data_to_protect);
      Monitor.Wait  (data_to_protect);
      … read out protected data
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  }
```

```
static void Writer()
  { try {
      Monitor.Enter (data_to_protect);
      … write protected data
      Monitor.Pulse (data_to_protect);
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  }
```

Centralized synchronization

Monitors in Visual C++

```
using namespace System;
using namespace System::Threading
private: integer data_to_protect;
```

```
void Reader()
  { try {
      Monitor::Enter (data_to_protect);
      Monitor::Wait  (data_to_protect);
      … read out protected data
    }
    finally {
      Monitor::Exit  (data_to_protect);
    }
  };
```

```
void Writer()
  { try {
      Monitor::Enter (data_to_protect);
      … write protected data
      Monitor::Pulse (data_to_protect);
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  };
```

Centralized synchronization

Monitors in Visual Basic

```
Imports System
Imports System.Threading
Private Dim data_to_protect As Integer = 0

Public Sub Reader
    Try
      Monitor.Enter (data_to_protect)
      Monitor.Wait  (data_to_protect)
      … read out protected data
    Finally
      Monitor.Exit  (data_to_protect)
    End Try
End Sub
```

```
Public Sub Writer
    Try
      Monitor.Enter (data_to_protect)
      … write protected data
      Monitor.Pulse (data_to_protect)
    Finally
      Monitor.Exit  (data_to_protect)
    End Try
End Sub
```

Centralized synchronization

Monitors in Java

```
Monitor mon = new Monitor();

Monitor.Condition Condvar = mon.new Condition();
```

```
public void reader
   throws InterruptedException {
      mon.enter();
      Condvar.await();
      … read out protected data
      mon.leave();
    }
```

```
public void writer
   throws InterruptedException {
      mon.enter();
      … write protected data
      Condvar.signal();
      mon.leave();
   }
```

… the Java library monitor connects data or condition variables to the monitor by convention only!

Centralized synchronization

Monitors in Java

(by means of language primitives)

Java provides two mechanisms to construct a monitors-like structure:

- **Synchronized methods and code blocks:**
  all methods and code blocks which are using the `synchronized` tag are mutually exclusive with respect to the addressed class.

- **Notification methods**:
  `wait`, `notify`, and `notifyAll` can be used only in synchronized regions and are waking any or all threads, which are waiting in the same synchronized object.

Centralized synchronization

Monitors in Java

(by means of language primitives)

Considerations:

1. Synchronized methods and code blocks:

- In order to implement a monitor *all* methods in an object need to be synchronized.
  ☞ any other standard method can break a Java monitor and enter at any time.
- Methods outside the monitor-object can synchronize at this object.
  ☞ it is impossible to analyse a Java monitor locally, since lock accesses can exist all over the system.
- Static data is shared between all objects of a class.
  ☞ access to static data need to be synchronized with all objects of a class.

Synchronize either in static synchronized blocks: `synchronized (this.getClass()) {…}`
or in static methods: `public synchronized static <method> {…}`

Centralized synchronization

Monitors in Java

(by means of language primitives)

Considerations:

2. Notification methods: `wait`, `notify`, and `notifyAll`

- `wait` suspends the thread and releases the local lock only
  - ☞ nested `wait`-calls will keep all enclosing locks.
- `notify` and `notifyAll` do not release the lock!
  - ☞ methods, which are activated via notification need to wait for lock-access.
- Java does *not* require any specific release order (like a queue) for `wait`-suspended threads
  - ☞ livelocks are not prevented at this level (in opposition to RT-Java).
- There are no explicit conditional variables associated with the monitor or data.
  - ☞ notified threads need to wait for the lock to be released **and** to re-evaluate its entry condition.

Centralized synchronization

Monitors in Java

(by means of language primitives)

Standard monitor solution:

- declare the monitored data-structures private to the monitor object (non-static).
- introduce a class ConditionVariable:

```
public class ConditionVariable {
   public boolean wantToSleep = false;
}
```

- introduce synchronization-scopes in monitor-methods:

  ☞ synchronize on the *adequate* conditional variables *first* and

  ☞ synchronize on the *adequate* monitor-object *second*.

- make sure that *all* methods in the monitor are implementing the correct synchronizations.
- make sure that *no other method* in the whole system is synchronizing on or interfering with this monitor-object in any way ☞ by convention.

Centralized synchronization

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
public class ReadersWriters {

   private int     readers        = 0;
   private int     waitingReaders = 0;
   private int     waitingWriters = 0;
   private boolean writing        = false;

   ConditionVariable OkToRead  = new ConditionVariable ();
   ConditionVariable OkToWrite = new ConditionVariable ();
…
```

Centralized synchronization

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
…  public void StartWrite () throws InterruptedException {
      synchronized (OkToWrite) {
         synchronized (this) {
            if (writing | readers > 0) {
               waitingWriters++;
               OkToWrite.wantToSleep = true;
            } else {
               writing = true;
               OkToWrite.wantToSleep = false;
            }
         }
         if (OkToWrite.wantToSleep) OkToWrite.wait ();
      }
   } …
```

Centralized synchronization

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
…  public void StopWrite () {
      synchronized (OkToRead) {
         synchronized (OkToWrite) {
            synchronized (this) {
               if (waitingWriters > 0) {
                  waitingWriters--;
                  OkToWrite.notify (); // wakeup one writer
               } else {
                  writing = false;
                  OkToRead.notifyAll (); // wakeup all readers
                  readers = waitingReaders;
                  waitingReaders = 0;
               }
   } } } } …
```

Centralized synchronization

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
…  public void StartRead () throws InterruptedException {
      synchronized (OkToRead) {
         synchronized (this) {
            if (writing | waitingWriters > 0) {
               waitingReaders++;
               OkToRead.wantToSleep = true;
            } else {
               readers++;
               OkToRead.wantToSleep = false;
            }
         }
         if (OkToRead.wantToSleep) OkToRead.wait ();
      }
   } …
```

Centralized synchronization

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
…  public void StopRead () {
      synchronized (OkToWrite) {
         synchronized (this) {
            readers--;
            if (readers == 0 & waitingWriters > 0) {
               waitingWriters--;
               OkToWrite.notify ();
            }
         }
      }
   }
}
```

Centralized synchronization

Monitors in Java

Per Brinch Hansen (1938-2007) in 1999:

Java's most serious mistake was the decision to use the sequential part of the language to implement the run-time support for its parallel features. It strikes me as absurd to write a compiler for the sequential language concepts only and then attempt to skip the much more difficult task of implementing a secure parallel notation. This wishful thinking is part of Java's unfortunate inheritance of the insecure C language and its primitive, error-prone library of threads methods.

"Per Brinch Hansen is one of a handful of computer pioneers who was responsible for advancing both operating systems development and concurrent programming from ad hoc techniques to systematic engineering disciplines." (from his IEEE 2002 Computer Pioneer Award)

Centralized synchronization

Object-orientation and synchronization

Since mutual exclusion, notification, and condition synchronization schemes need to be designed and analyzed considering the implementation of all involved methods and guards:

☞ New methods cannot be added without re-evaluating the class!

Re-usage concepts of object-oriented programming do not translate to synchronized classes (e.g. monitors) and thus need to be considered carefully.

☞ The parent class might need to be adapted
in order to suit the global synchronization scheme.

☞ **Inheritance anomaly** (Matsuoka & Yonezawa '93)

Methods to design and analyse expandible synchronized systems exist, yet they are complex and not offered in any concurrent programming language.
Alternatively, inheritance can be banned in the context of synchronization (e.g. Ada).

Centralized synchronization

Monitors in POSIX, Visual C++, C#, Visual Basic & Java

- ☞ All provide lower-level primitives for the construction of monitors.
- ☞ All rely on **convention** rather than compiler checks.
- ☞ Visual C++, C+ & Visual Basic offer data-encapsulation and connection to the monitor.
- ☞ Java offers data-encapsulation (yet not with respect to a monitor).
- ☞ POSIX (being a collection of library calls) does not provide any data-encapsulation by itself.

☞ Extreme care must be taken when employing object-oriented programming and synchronization (incl. monitors)

Centralized synchronization

Nested monitor calls

Assuming a thread in a monitor is calling an operation in another monitor and is suspended at a conditional variable there:

☞ the called monitor is aware of the suspension and allows other threads to enter.

☞ the calling monitor is possibly not aware of the suspension and *keeps its lock*!

☞ the unjustified locked calling monitor reduces the system performance and leads to potential deadlocks.

Suggestions to solve this situation:

- Maintain the lock anyway: e.g. POSIX, Java
- Prohibit nested monitor calls: e.g. Modula-1
- Provide constructs which specify the release of a monitor lock for remote calls, e.g. Ada

Centralized synchronization

Criticism of monitors

- Mutual exclusion is solved elegantly and safely.
- Conditional synchronization is on the level of semaphores still
  - ☞ all criticism about semaphores applies inside the monitors

☞ Mixture of low-level and high-level synchronization constructs.

Centralized synchronization

Synchronization by protected objects

Combine

the **encapsulation** feature of monitors

with

the **coordinated entries** of conditional critical regions

to:

☞ Protected objects

- **All** controlled data and operations are **encapsulated**.
- Operations are **mutual exclusive** (with exceptions for read-only operations).
- **Guards** (predicates) are **syntactically attached** to entries.
- **No** protected data is accessible (other than by the defined operations).
- **Fairness** inside operations is guaranteed by **queuing** (according to their priorities).
- **Fairness** across all operations is guaranteed by the "internal progress first" rule.
- Re-blocking provided by **re-queuing** to entries (no internal condition variables).

Centralized synchronization

Synchronization by protected objects

(Simultaneous read-access)

Some read-only operations do not need to be mutually exclusive:

```
protected type Shared_Data (Initial : Data_Item) is
   function  Read return Data_Item;
   procedure Write (New_Value : Data_Item);
private
   The_Data : Data_Item := Initial;
end Shared_Data_Item;
```

- **protected functions** can have 'in' parameters only
  and are not allowed to alter the private data (enforced by the compiler).

☞ **protected functions** allow *simultaneous access* (but mutual exclusive with other operations).

… there is no defined priority between functions and other protected operations in Ada.

Centralized synchronization

Synchronization by protected objects

(Condition synchronization: entries & barriers)

Condition synchronization is realized in the form of **protected procedures** combined with boolean predicates (**barriers**): ☞ called **entries** in Ada:

```
Buffer_Size : constant Integer := 10;

type    Index    is mod Buffer_Size;
subtype Count    is Natural range 0 .. Buffer_Size;
type    Buffer_T is array (Index) of Data_Item;

protected type Bounded_Buffer is

   entry Get (Item : out Data_Item);
   entry Put (Item :     Data_Item);

private
   First  : Index := Index'First;
   Last   : Index := Index'Last;
   Num    : Count := 0;
   Buffer : Buffer_T;
end Bounded_Buffer;
```

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Condition synchronization: entries & barriers)

```
protected body Bounded_Buffer is
   entry Get (Item : out Data_Item) when Num > 0 is
      begin
         Item  := Buffer (First);
         First := First + 1;
         Num   := Num - 1;
     end Get;
   entry Put (Item : Data_Item) when Num < Buffer_Size is
      begin
         Last          := Last + 1;
         Buffer (Last) := Item;
         Num           := Num + 1;
      end Put;
end Bounded_Buffer;
```

Centralized synchronization

Synchronization by protected objects

(Withdrawing entry calls)

```
Buffer : Bounded_Buffer;

select
   Buffer.Put (Some_Data);
or
   delay 10.0;
   -- do something after 10 s.
end select;

select
   Buffer.Get (Some_Data);
else
   -- do something else
end select;
```

Centralized synchronization

Synchronization by protected objects

(Withdrawing entry calls)

```
Buffer : Bounded_Buffer;

select
   Buffer.Put (Some_Data);
or
   delay 10.0;
   -- do something after 10 s.
end select;

select
   Buffer.Get (Some_Data);
else
   -- do something else
end select;
```

```
select
   Buffer.Get (Some_Data);
then abort
   -- meanwhile try something else
end select;

select
   delay 10.0;
then abort
   Buffer.Put (Some_Data);
   -- try to enter for 10 s.
end select;
```

Centralized synchronization

Synchronization by protected objects

(Barrier evaluation)

Barrier in protected objects need to be evaluated only on two occasions:

- on *creating a protected object,*
  all barrier are evaluated according to the initial values of the internal, protected data.
- on *leaving a protected procedure or entry,*
  all potentially altered barriers are re-evaluated.

Alternatively an implementation may choose to evaluate barriers on those two occasions:

- on *calling a protected entry,*
  the one associated barrier is evaluated.
- on *leaving a protected procedure or entry,*
  all potentially altered barriers with tasks queued up on them are re-evaluated.

Barriers are not evaluated *while inside* a protected object or *on leaving a protected function*.

Synchronization by protected objects

(Operations on entry queues)

The count attribute indicates the number of tasks waiting at a specific queue:

```
protected Block_Five is
   entry Proceed;
private
   Release : Boolean := False;
end Block_Five;
```

```
protected body Block_Five is
   entry Proceed
      when Proceed'count > 5
           or Release is
   begin
      Release := Proceed'count > 0;
   end Proceed;
end Block_Five;
```

Centralized synchronization

Synchronization by protected objects

(Operations on entry queues)

The count attribute indicates the number of tasks waiting at a specific queue:

```
protected type Broadcast is

   entry Receive   (M: out Message);
   procedure Send (M:     Message);

private
   New_Message : Message;
   Arrived      : Boolean := False;

end Broadcast;
```

```
protected body Broadcast is

   entry Receive (M: out Message)
      when Arrived is

   begin
      M        := New_Message
      Arrived := Receive'count > 0;
   end Proceed;

   procedure Send (M: Message) is

   begin
     New_Message := M;
     Arrived      := Receive'count > 0;
   end Send;
end Broadcast;
```

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

Additional, essential primitives for concurrent control flows:

- **Entry families**:
  A protected entry declaration can contain
  a discrete subtype *selector*, which can be *evaluated* by the barrier (other parameters cannot be evaluated by barriers) and implements an *array* of protected entries.

- **Requeue facility**:
  Protected operations can use '`requeue`' to redirect tasks to other *internal*, *external*, or *private* entries. The current protected operation is finished and the lock on the object is *released*.

'Internal progress first'-rule: external tasks are only considered for queuing on barriers once no internally requeued task can be progressed any further!

- **Private entries**:
  Protected entries which are not accessible from outside the protected object, but can be employed as destinations for requeue operations.

Centralized synchronization

Synchronization by protected objects

(Entry families)

```
package Modes is

  type Mode_T is
    (Takeoff, Ascent, Cruising,
     Descent, Landing);

  protected Mode_Gate is
   procedure Set_Mode (Mode: Mode_T);
   entry Wait_For_Mode (Mode_T);

  private
   Current_Mode : Mode_Type := Takeoff;
  end Mode_Gate;

end Modes;
```

```
package body Modes is

  protected body Mode_Gate is
    procedure Set_Mode
      (Mode: Mode_T) is

  begin
    Current_Mode := Mode;
  end Set_Mode;

  entry Wait_For_Mode
      (for Mode in Mode_T)
      when Current_Mode = Mode is

    begin null;
    end Wait_For_Mode;

  end Mode_Gate;

end Modes;
```

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

How to moderate the flow of incoming calls to a busy server farm?

```
type Urgency     is (urgent, not_so_urgent);
type Server_Farm is (primary, secondary);
protected Pre_Filter is
   entry Reception (U : Urgency);
private
   entry Server (Server_Farm) (U : Urgency);
end Pre_Filter;
```

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

```
protected body Pre_Filter is

   entry Reception (U : Urgency)
     when Server (primary)'count = 0 or else Server (secondary)'count = 0 is

   begin

      If U = urgent and then Server (primary)'count = 0 then
         requeue Server (primary);

      else
         requeue Server (secondary);
      end if;

   end Reception;

   entry Server (for S in Server_Farm) (U : Urgency) when True is

   begin null; -- might try something even more useful
   end Server;

end Pre_Filter;
```

Centralized synchronization

Synchronization by protected objects

(Restrictions for protected operations)

All code inside a protected procedure, function or entry is bound to non-blocking operations.

Thus the following operations are prohibited:

- `entry` call statements
- `delay` statements
- `task` creations or activations
- `select` statements
- `accept` statements
- … as well as calls to sub-programs which contain any of the above

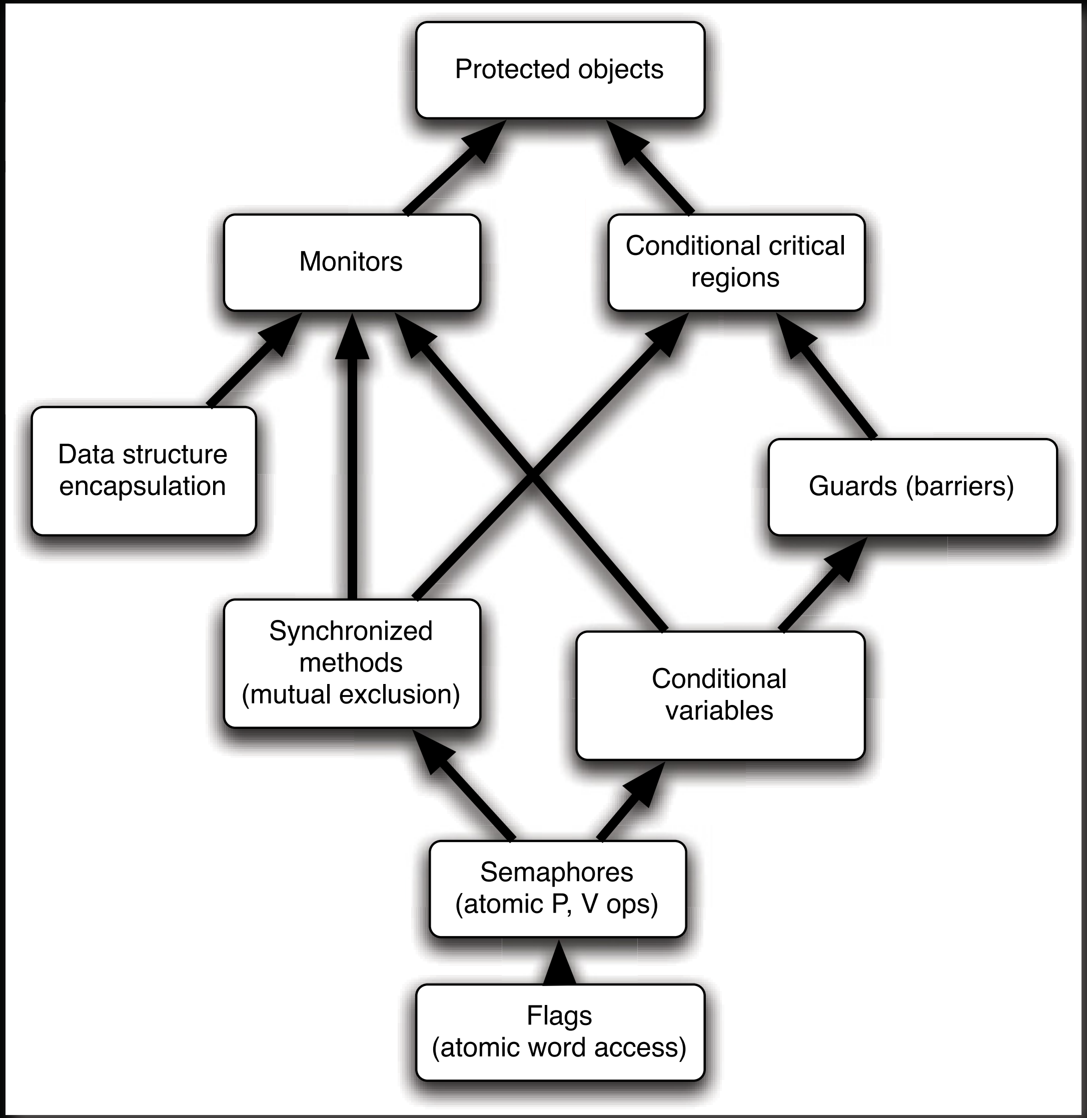
☞ The `requeue` facility allows for a potentially blocking operation, *and* releases the current lock!

Shared memory based synchronization

General

Criteria:

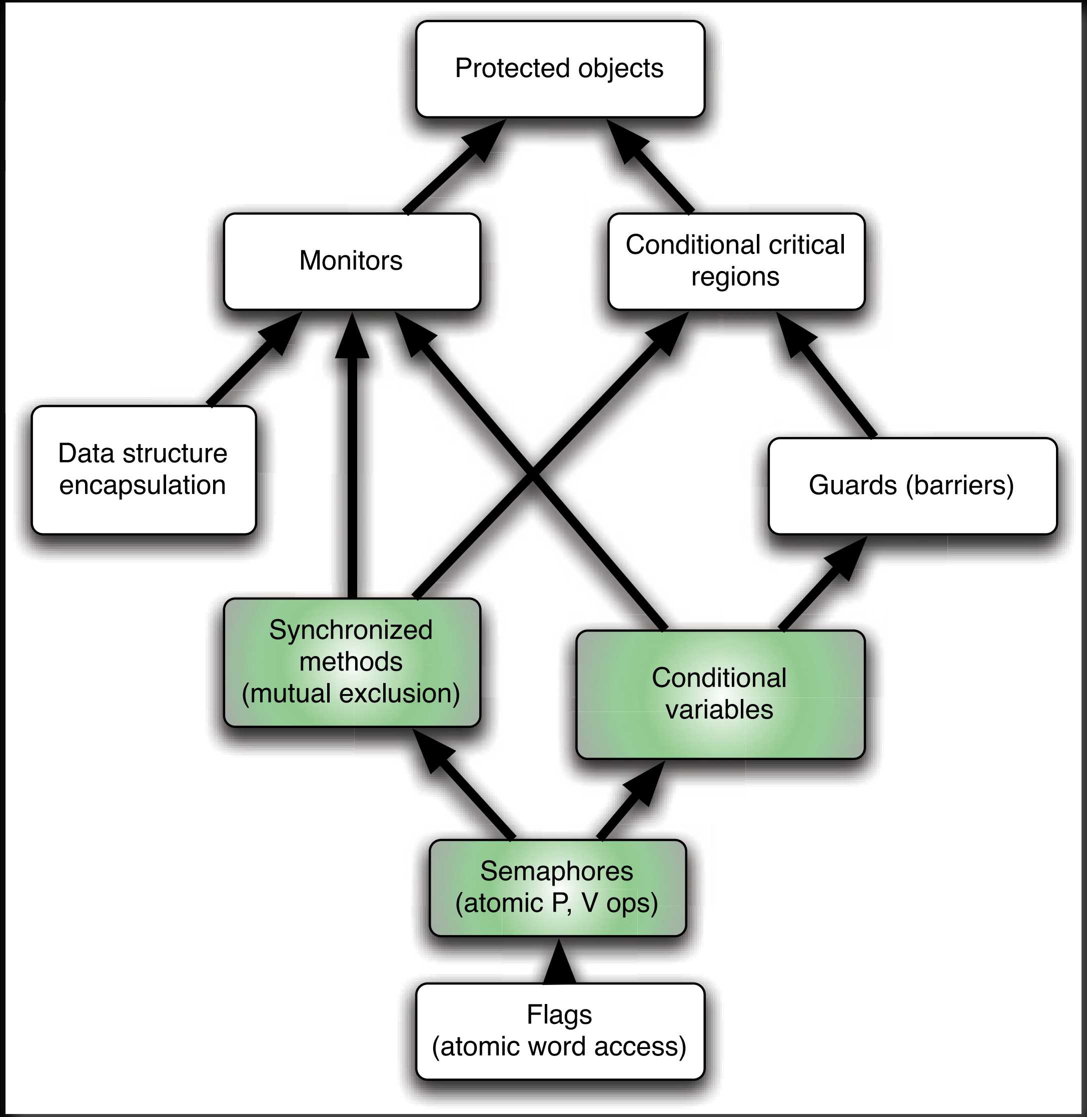
- *Levels of abstraction*
- *Centralized versus distributed*
- *Support for automated (compiler based) consistency and correctness validation*
- *Error sensitivity*
- *Predictability*
- *Efficiency*


Protected objects
Monitors
Conditional critical regions
Data structure encapsulation
Guards (barriers)
Synchronized methods (mutual exclusion)
Conditional variables
Semaphores (atomic P, V ops)
Flags (atomic word access)

Shared memory based synchronization

POSIX

- *All low level constructs available*
- *Connection with the actual data-structures by means of convention only*
- *Extremely error-prone*
- *Degree of non-determinism introduced by the 'release some' semantic*
- *'C' based*
- *Portable*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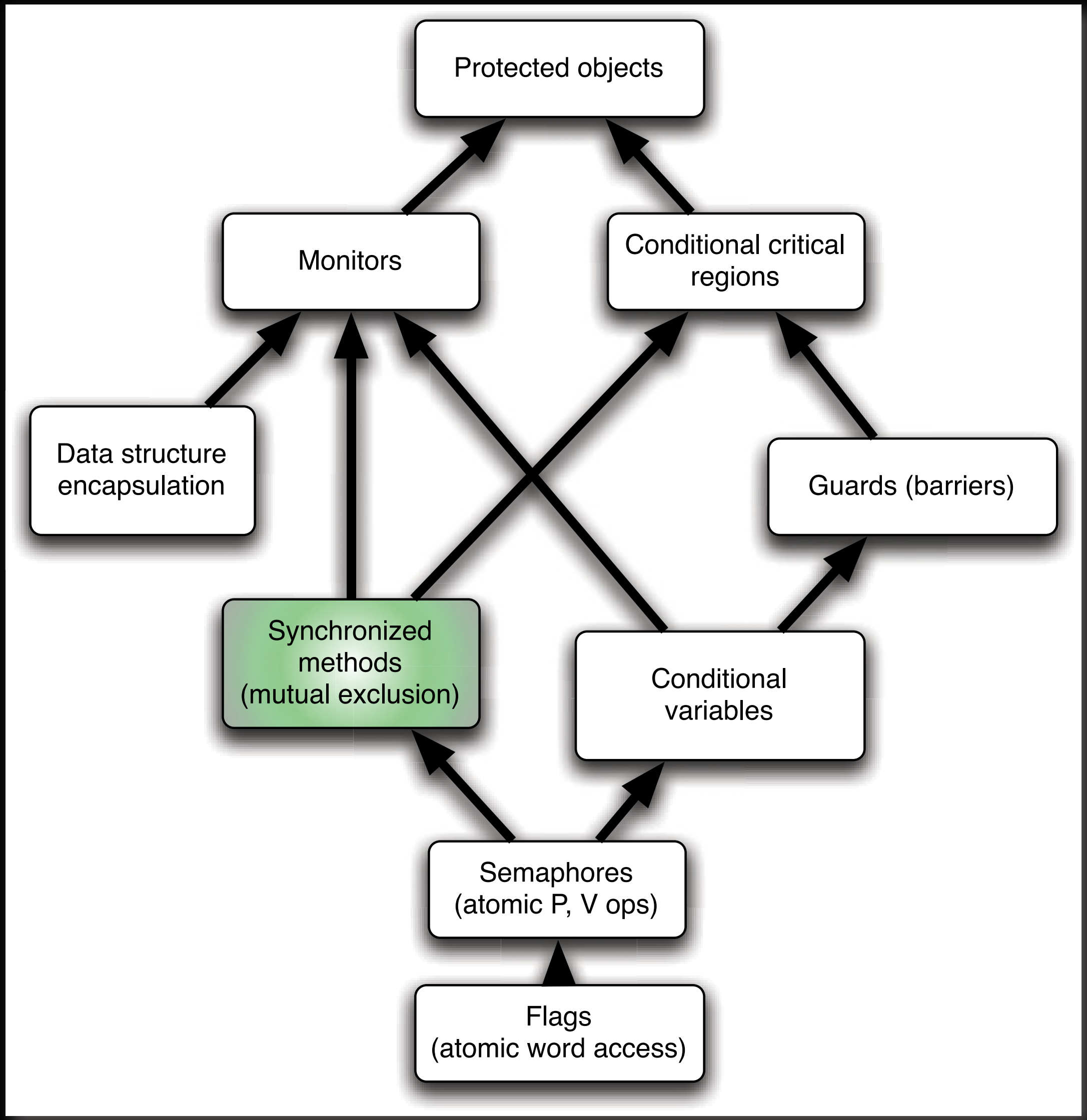
Shared memory based synchronization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Flags (atomic word access)

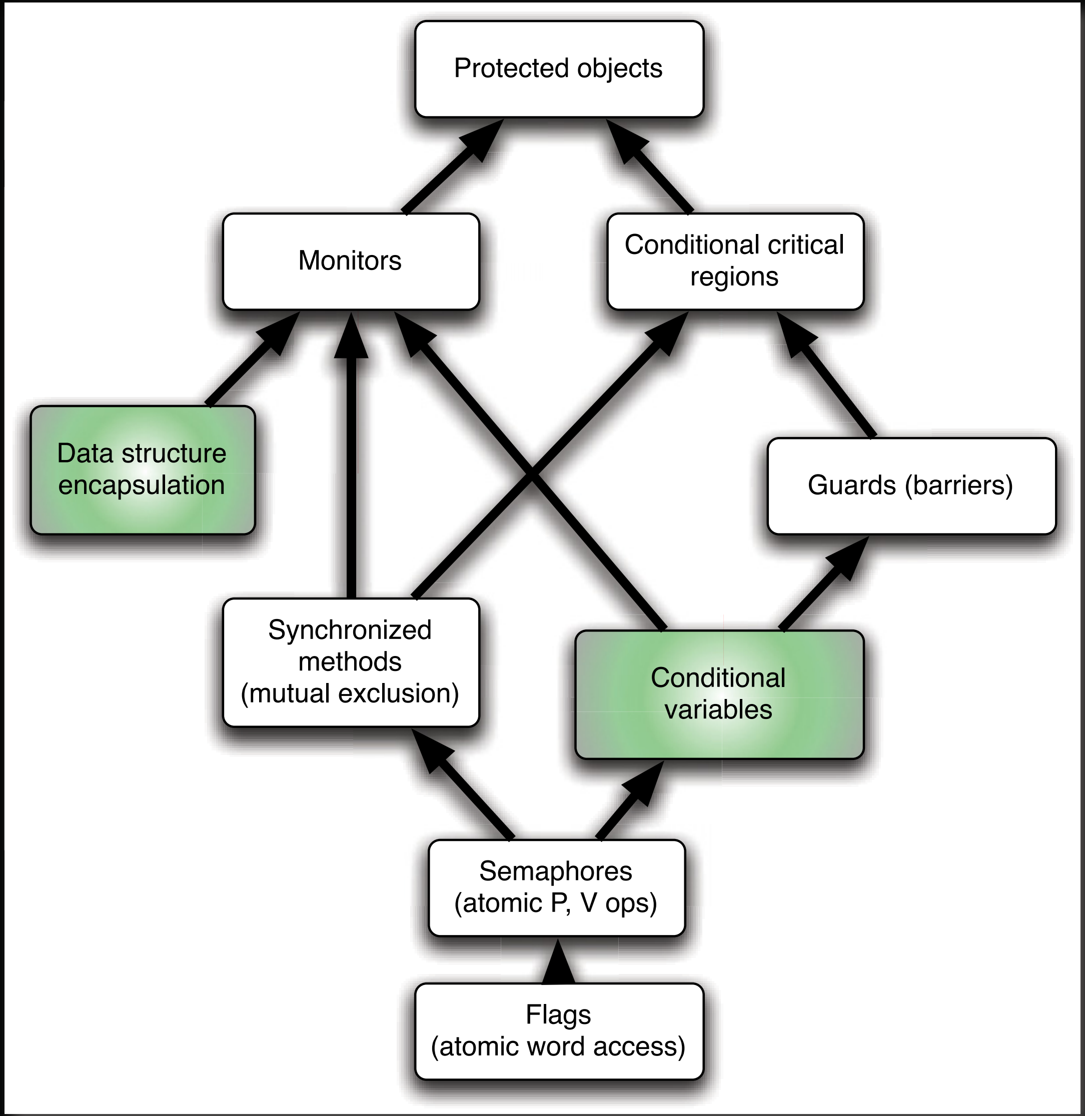
Java

- Mutual exclusion available.
- General notification feature (not connected to other locks, hence not a conditional variable)
- Universal object orientation makes local analysis hard or even impossible
- Mixture of high-level object oriented features and low level concurrency primitives

Shared memory based synchronization

C#, Visual C++, Visual Basic

- *Mutual exclusion via library calls (convention)*
- *Data is associated with the locks to protect it*
- *Condition variables related to the data protection locks*
- *Mixture of high-level object oriented features and low level concurrency primitives*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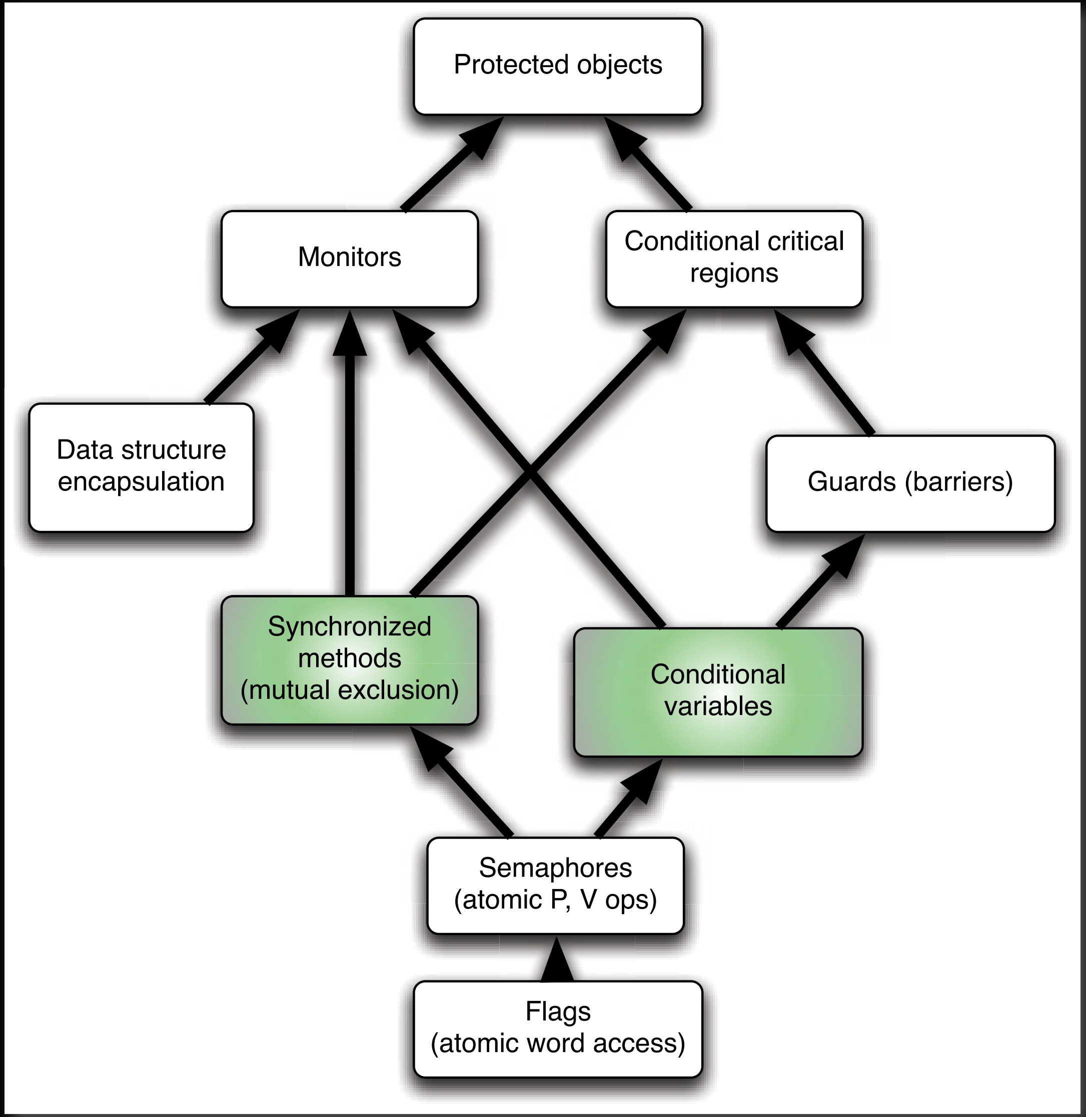
Shared memory based synchronization

C++14

- *Mutual exclusion in scopes*
- *Data is not strictly associated with the locks to protect it*
- *Condition variables related to the mutual exclusion locks*
- *Set of essential primitives without combining them in a syntactically strict form (yet?)*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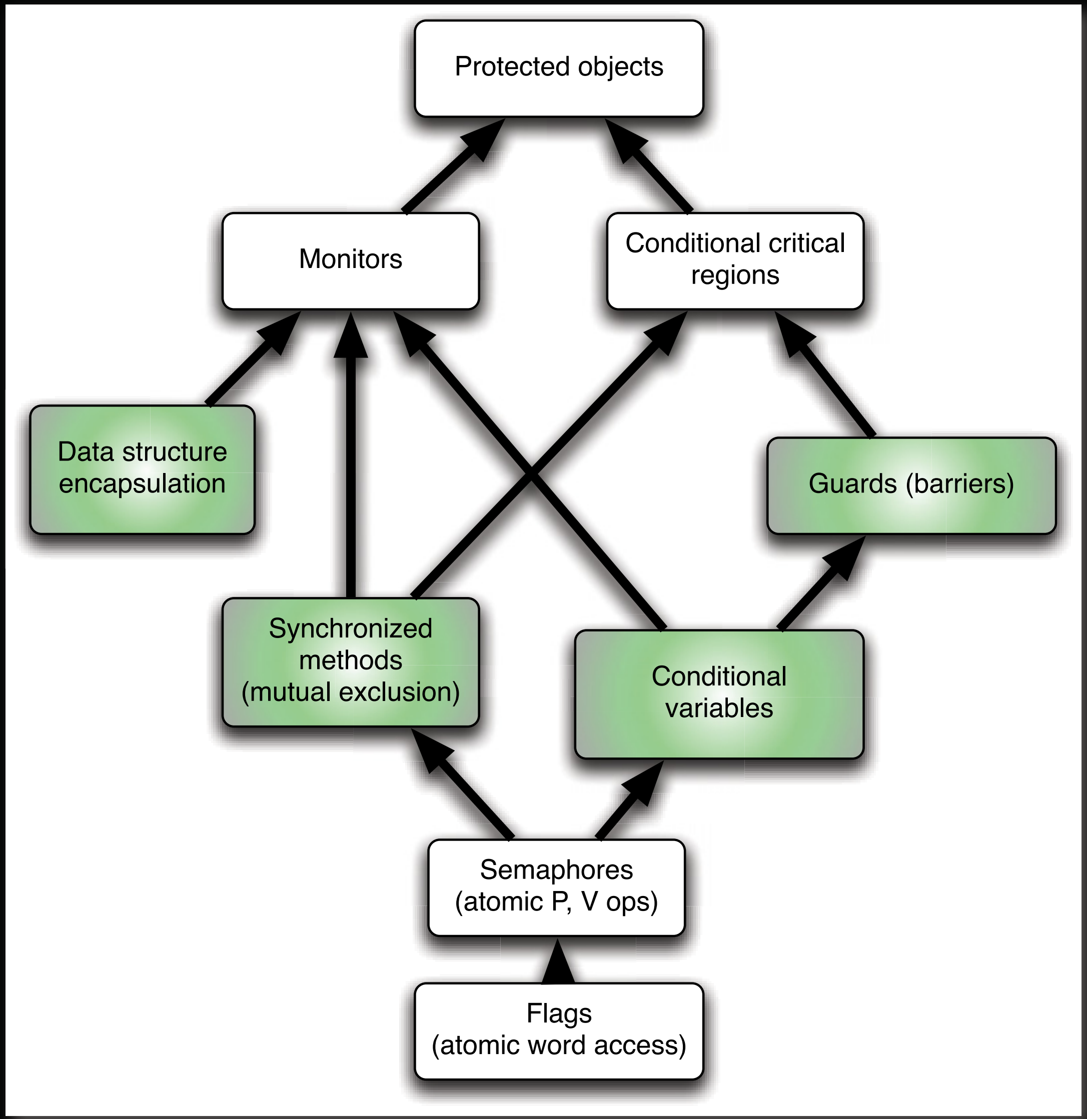
Shared memory based synchronization

Rust

- *Mutual exclusion in scopes*
- *Data is strictly associated with locks to protect it*
- *Condition variables related to the mutual exclusion locks*
- *Combined with the message passing semantics already a power set of tools.*
- *Concurrency features migrated to a standard library.*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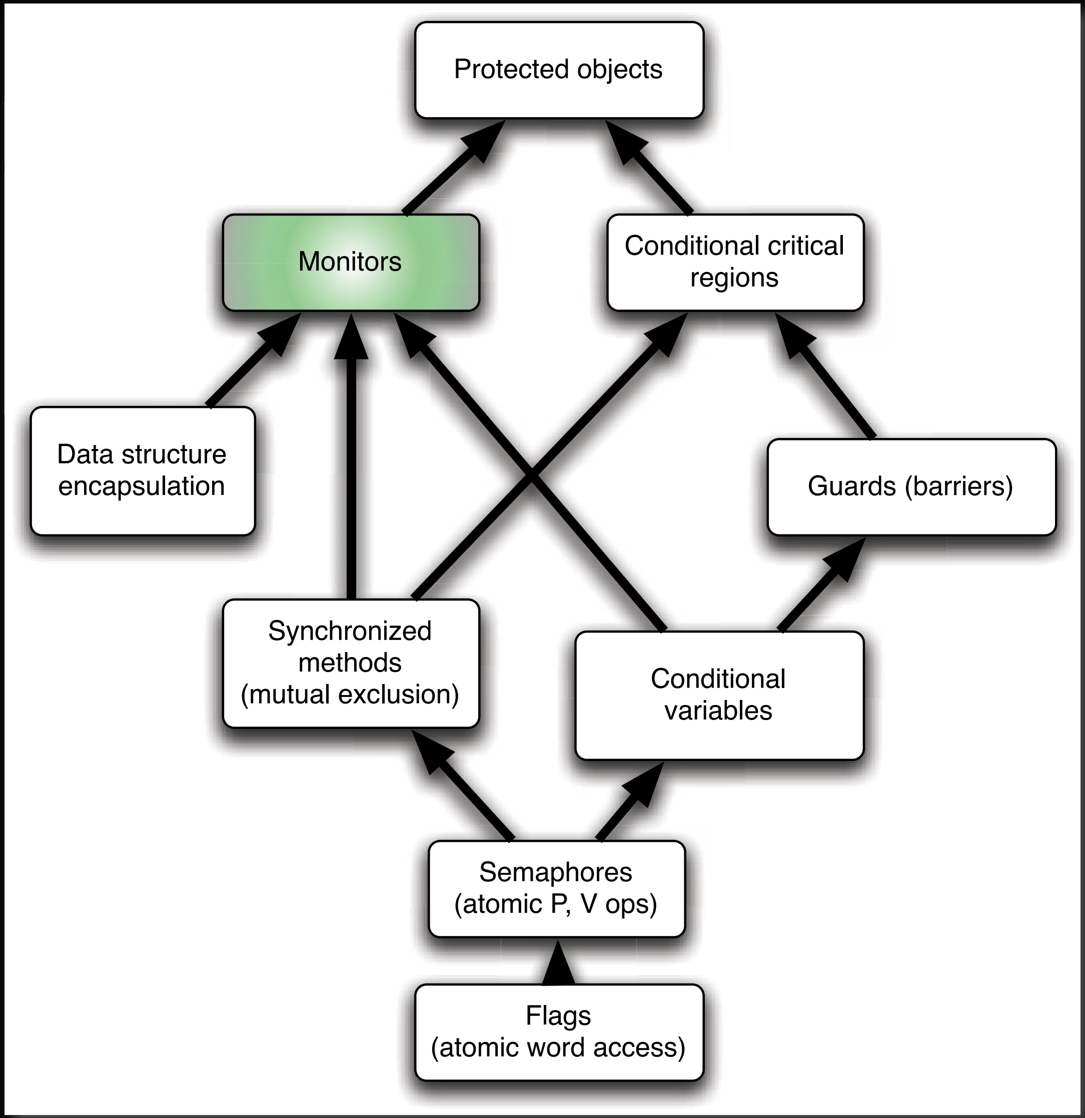
Shared memory based synchronization

Modula-1, Chill, Parallel Pascal, …

- *Full implementation of the Dijkstra / Hoare monitor concept*

The term **monitor** *appears in many other concurrent languages, yet it is usually not associated with an actual language primitive.*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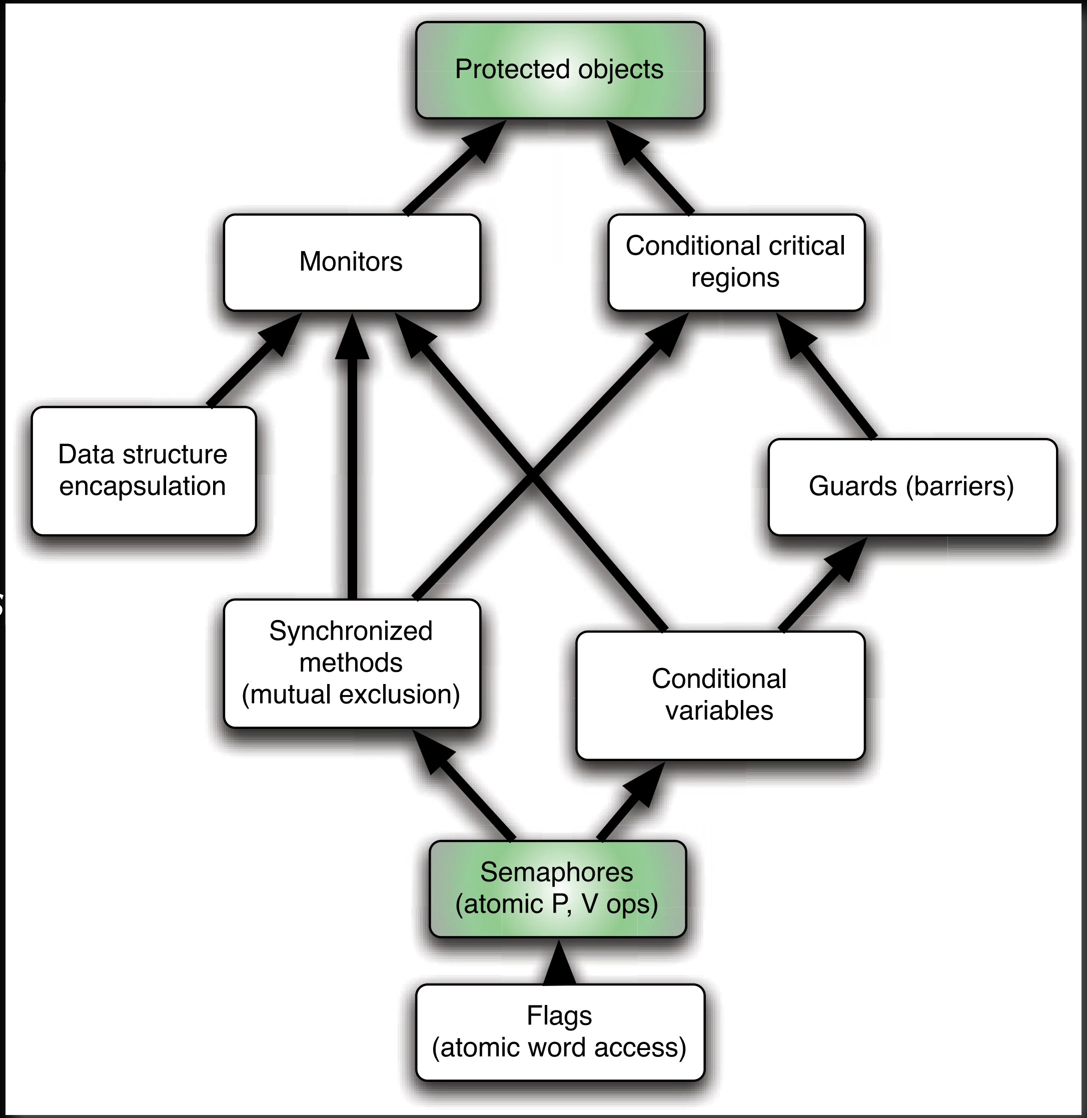
Shared memory based synchronization

Ada

- *High-level synchronization support which scales to large size projects.*
- *Full compiler support incl. potential deadlock analysis*
- *Low-Level semaphores for very special cases*

Ada has still
no mainstream competitor
in the field of explicit concurrency.
(2018)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High Performance Computing

Synchronization in large scale concurrency

High Performance Computing (HPC) emphasizes on keeping as many CPU nodes busy as possible:

☞ Avoid contention on sparse resources.

☞ Data is assigned to individual processes rather than processes synchronizing on data.

☞ Data integrity is achieved by keeping the CPU nodes in approximate “lock-step”, yet there is still a need to re-sync concurrent entities.

Traditionally this has been implemented using the Message Passing Interface (MPI) while implementing separate address spaces.

☞ Current approaches employ partitioned address spaces, i.e. memory spaces can overlap and be re-assigned. ☞ Chapel, Fortress, X10.

☞ Not all algorithms break down into independent computation slices and so there is a need for memory integrity mechanisms in shared/partitioned address spaces.

Current developments

Atomic operations in X10

X10 offers only atomic blocks in unconditional and conditional form.

- Unconditional atomic blocks are guaranteed to be non-blocking, which means that they cannot be nested and need to be implemented using roll-backs.
- Conditional atomic blocks can also be used as a pure notification system (similar to the Java notify method).
- Parallel statements (incl. parallel, i.e. unrolled 'loops').
- Shared variables (and their access mechanisms) are not defined.
- The programmer does not specify the scope of the locks (atomic blocks) but they are managed by the compiler/runtime environment.

☞ Code analysis algorithms are required in order to provide efficiently, otherwise the runtime environment needs to associate every atomic block with a *global* lock.

Current developments

Synchronization in Chapel

Chapel offers a variety of concurrent primitives:

- Parallel operations on data (e.g. concurrent array operations)
- Parallel statements (incl. parallel, i.e. unrolled 'loops')
- Parallelism can also be explicitly limited by serializing statements
- Atomic blocks for the purpose to construct atomic transactions
- Memory integrity needs to be programmed by means of synchronization statements (waiting for one or multiple control flows to complete) and/or atomic blocks

Further Chapel semantics are still forthcoming … so there is still hope for a stronger shared memory synchronization / memory integrity construct.

Message-based synchronization

Synchronization model

- Asynchronous
- Synchronous
- Remote invocation

Addressing (name space)

- direct communication
- mail-box communication

Message structure

- arbitrary
- restricted to ‘basic’ types
- restricted to un-typed communications

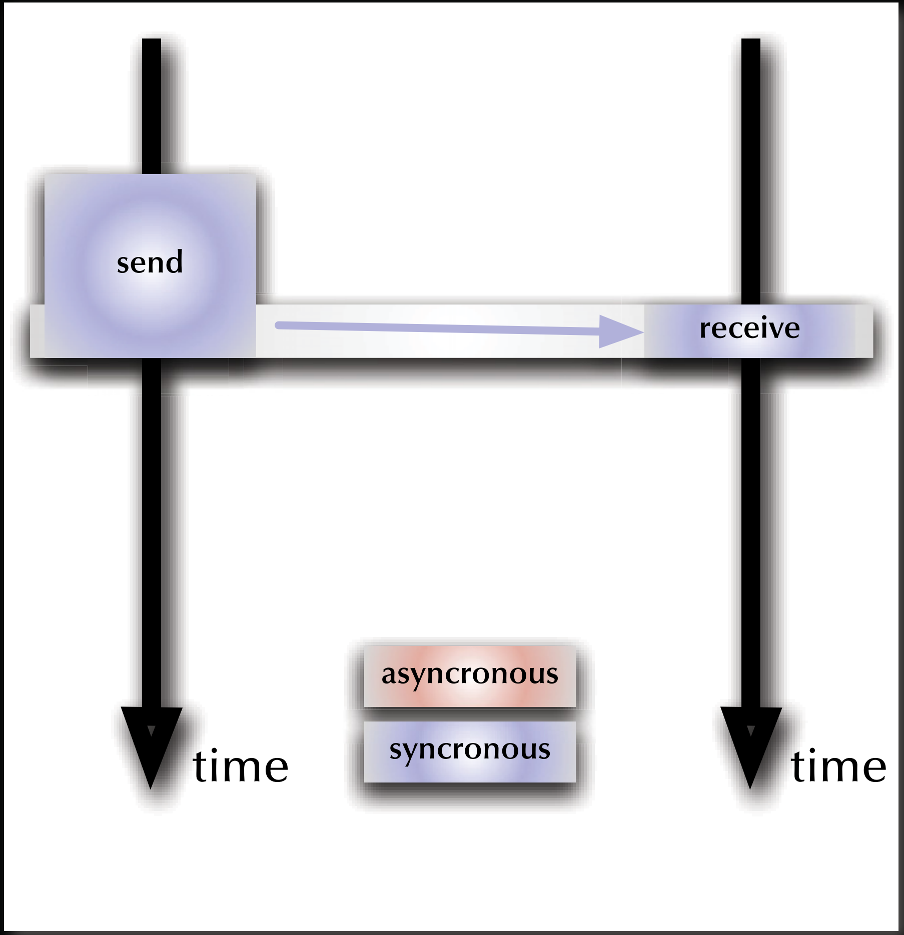
Message-based synchronization

Message protocols

Synchronous message
(sender waiting)

Delay the sender process until

- Receiver becomes available
- Receiver acknowledges reception



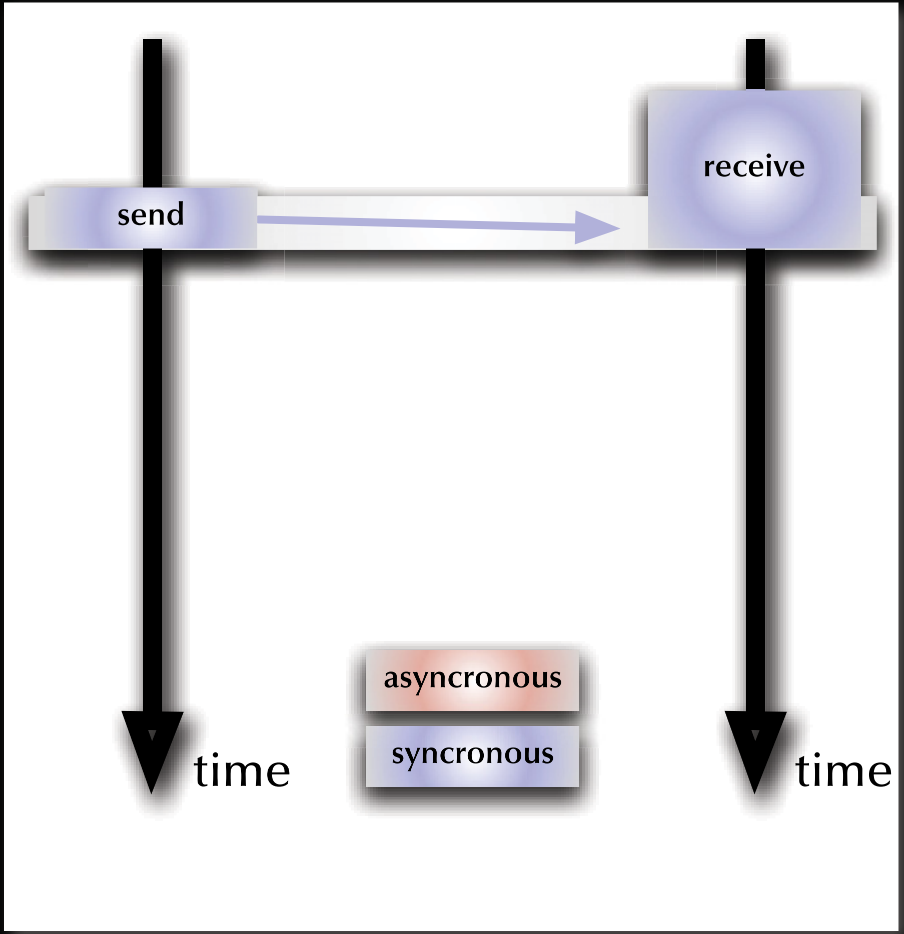
Message-based synchronization

Message protocols

Synchronous message
(receiver waiting)

Delay the receiver process until

- Sender becomes available
- Sender concludes transmission



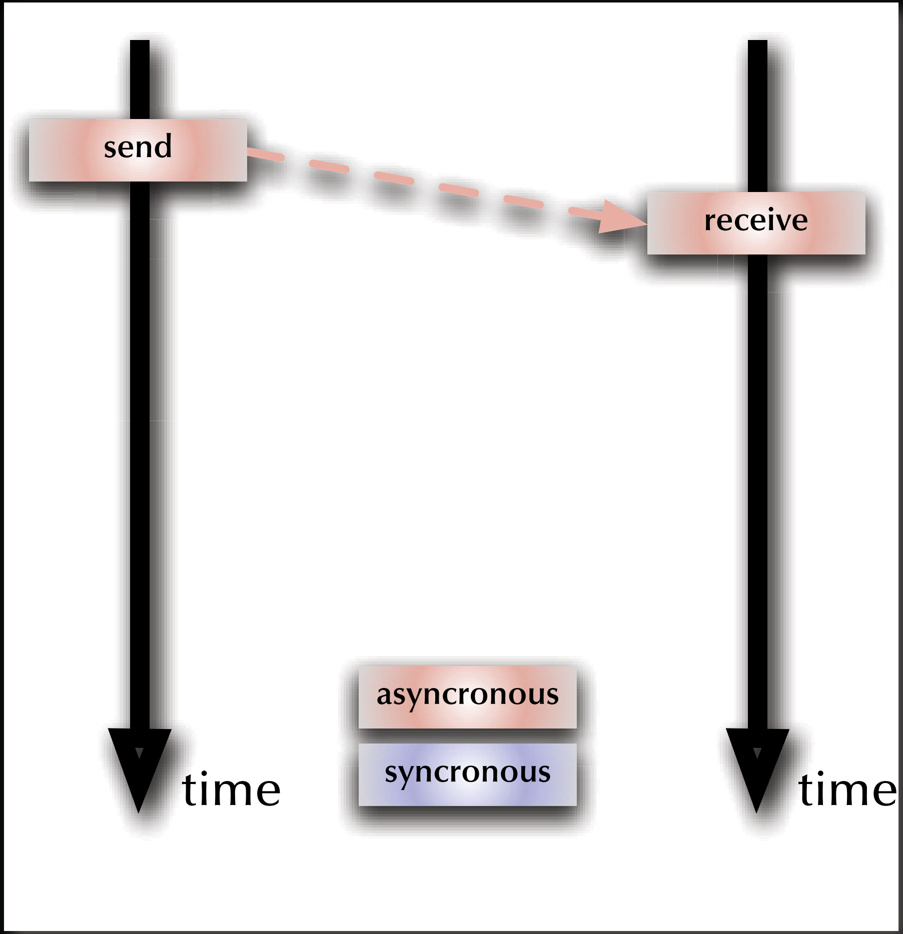
Message-based synchronization

Message protocols

Asynchronous message

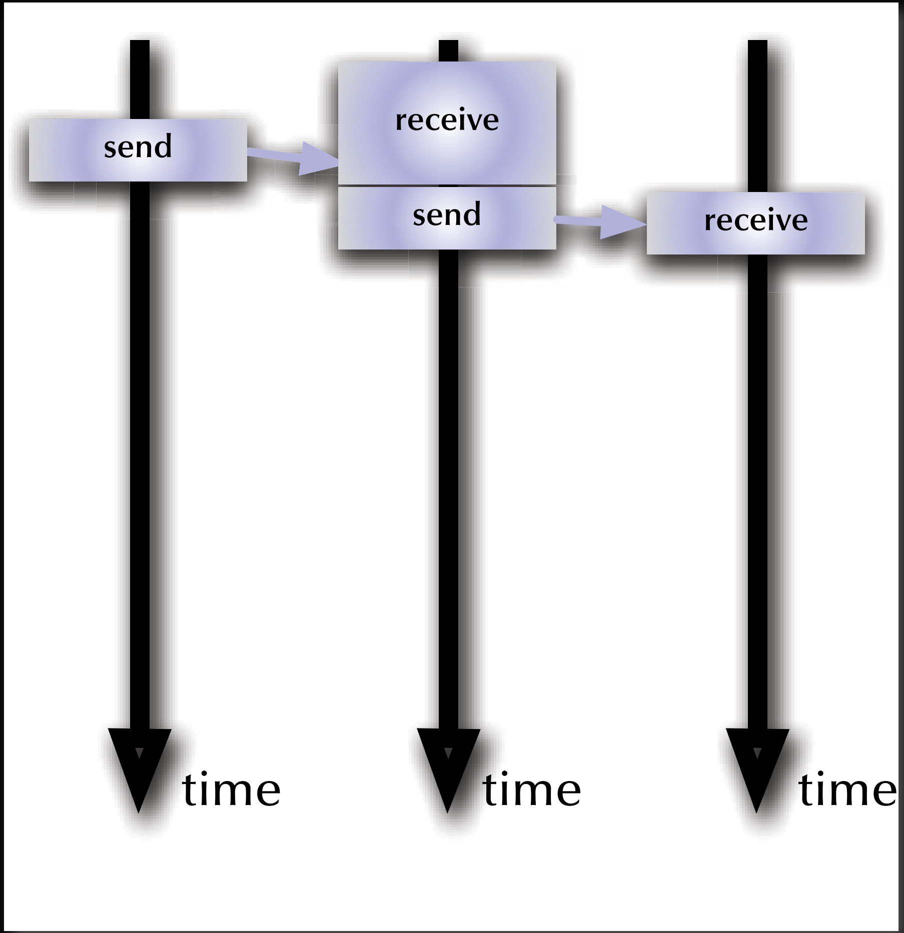
Neither the sender nor the receiver is blocked:

- Message is not transferred directly
- A buffer is required to store the messages
- Policy required for buffer sizes and buffer overflow situations



Message protocols

Asynchronous message (simulated by synchronous messages)



Introducing an intermediate process:

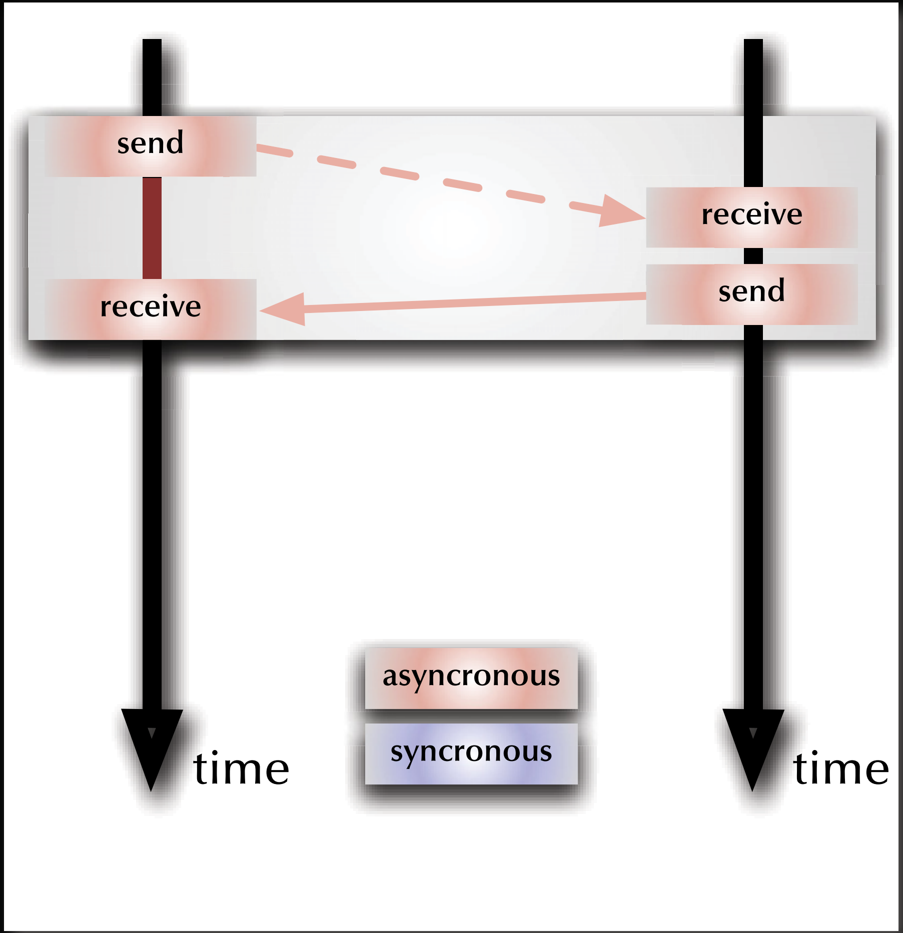
- Intermediate needs to be accepting messages at all times.
- Intermediate also needs to send out messages on request.

☞ While processes are blocked in the sense of synchronous message passing, they are not actually delayed as the intermediate is always ready.

Message-based synchronization

Message protocols

Synchronous message
(simulated by asynchronous messages)



Introducing two asynchronous messages:

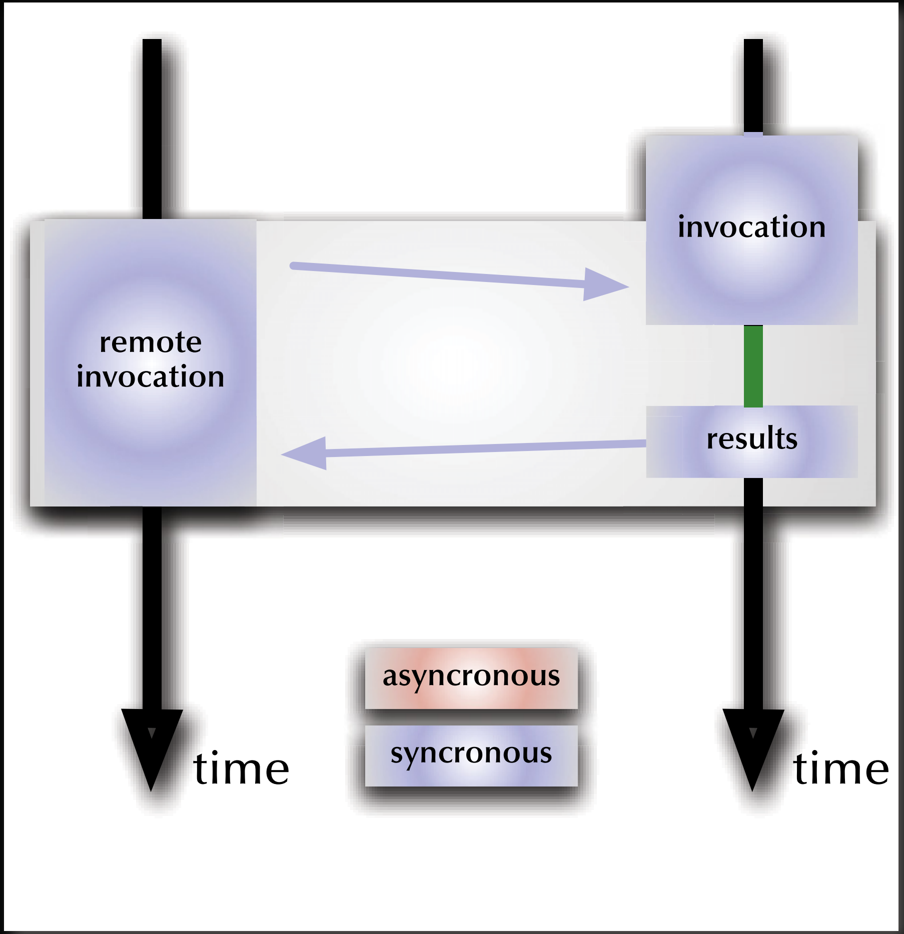
- Both processes voluntarily suspend themselves until the transaction is complete.
- As no immediate communication takes place, the processes are never actually synchronized.
- The sender (but not the receiver) process knows that the transaction is complete.

Message-based synchronization

Message protocols

Remote invocation

- Delay sender or receiver until the first rendezvous point
- Pass parameters
- Keep sender blocked while receiver executes the local procedure
- Pass results
- Release both processes out of the rendezvous

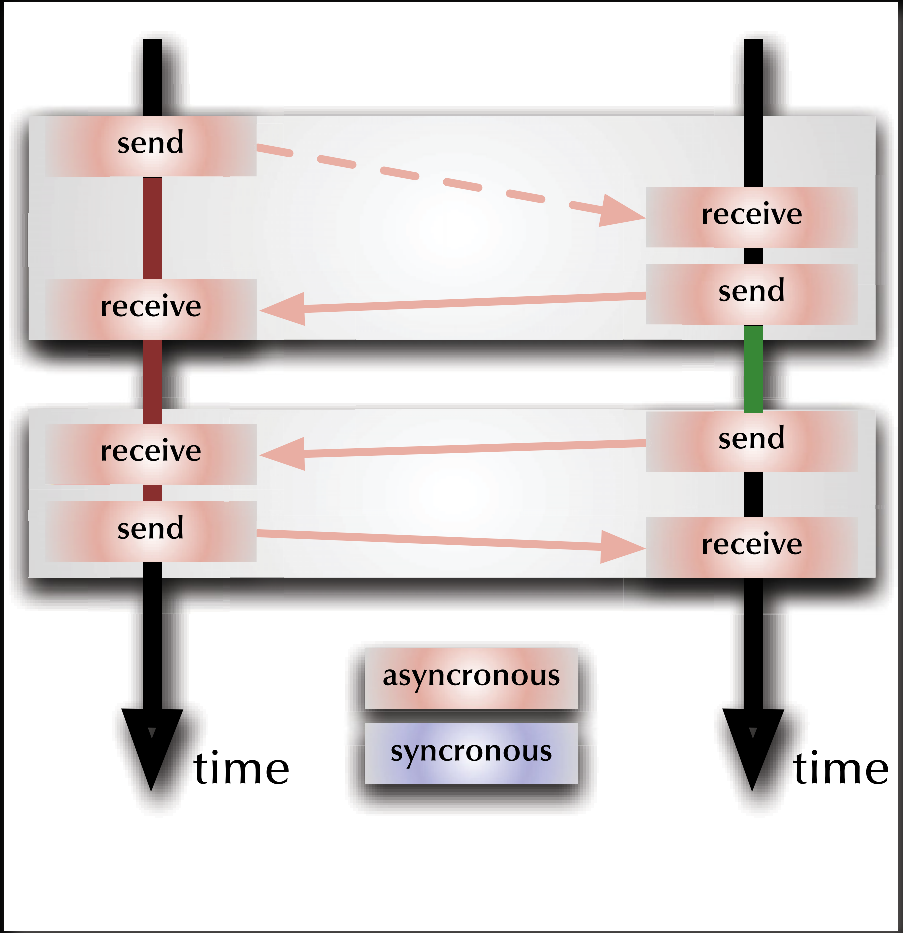


Message-based synchronization

Message protocols

Remote invocation
(simulated by asynchronous messages)

- Simulate two synchronous messages
- Processes are never actually synchronized



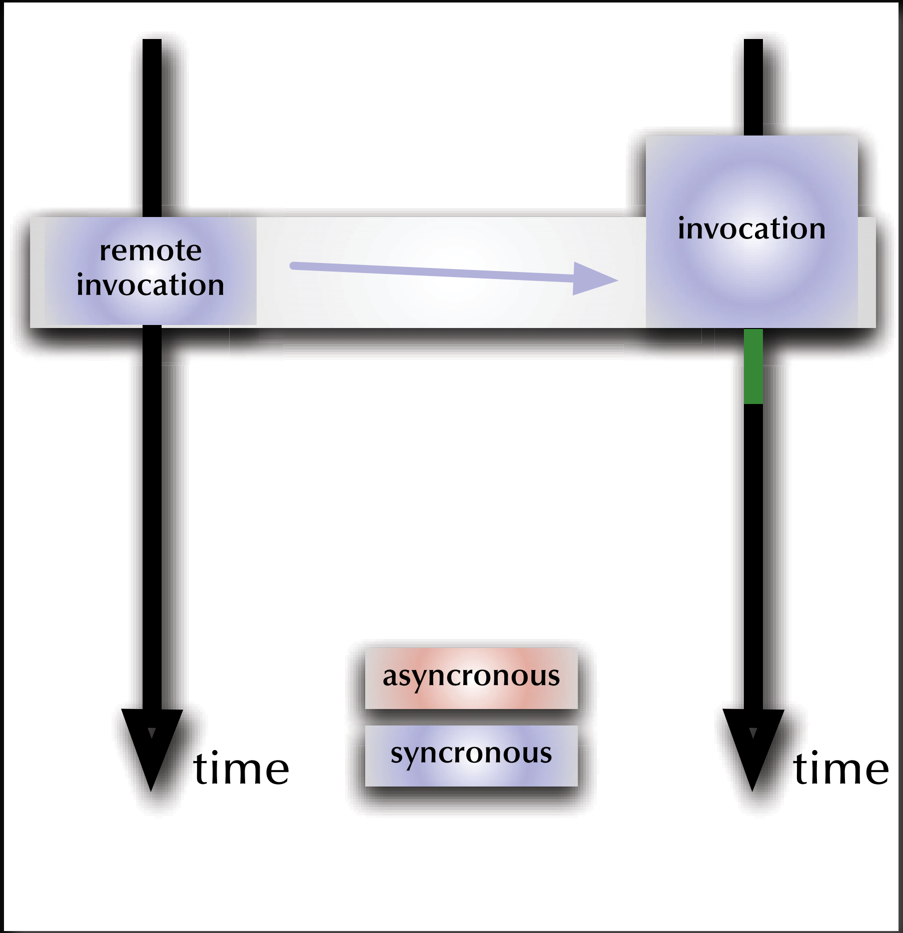
Message-based synchronization

Message protocols

Remote invocation (no results)

Shorter form of remote invocation which does not wait for results to be passed back.

- Still both processes are actually synchronized at the time of the invocation.

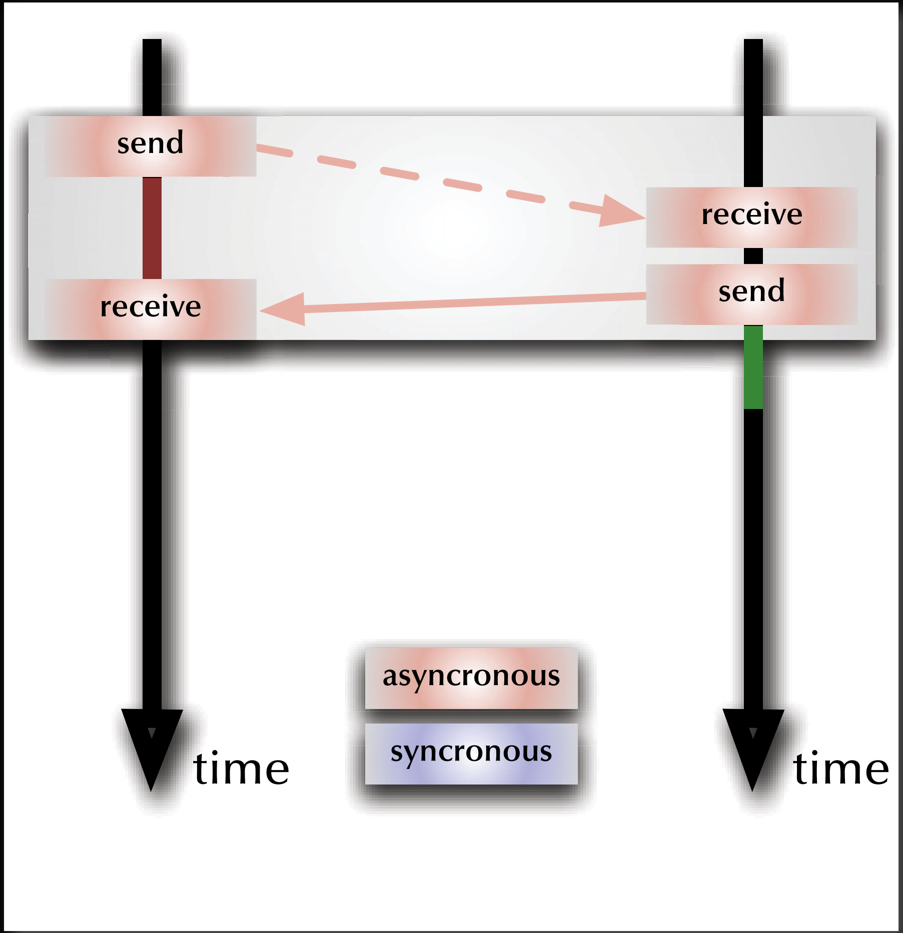


Message-based synchronization

Message protocols

Remote invocation (no results)
(simulated by asynchronous messages)

- Simulate one synchronous message
- Processes are never actually synchronized



Message-based synchronization

Synchronous vs. asynchronous communications

Purpose ‘**synchronization**’:	☞ synchronous messages / remote invocations
Purpose ‘**last message(s) only**’:	☞ asynchronous messages

☞ Synchronous message passing in distributed systems requires hardware support.

☞ Asynchronous message passing requires the usage of buffers and overflow policies.

Can both communication modes emulate each other?

Communication & Synchronization

Message-based synchronization

Synchronous vs. asynchronous communications

Purpose ‘**synchronization**’:	☞ synchronous messages / remote invocations
Purpose ‘**last message(s) only**’:	☞ asynchronous messages

☞ Synchronous message passing in distributed systems requires hardware support.

☞ Asynchronous message passing requires the usage of buffers and overflow policies.

Can both communication modes emulate each other?

- *Synchronous communications* are emulated by a combination of asynchronous messages in some systems (not identical with hardware supported synchronous communication).
- *Asynchronous communications* can be emulated in synchronized message passing systems by introducing a ‘buffer-task’ (de-coupling sender and receiver as well as allowing for broadcasts).

Message-based synchronization

Addressing (name space)

Direct versus indirect:

```
send     <message> to   <process-name>
wait for <message> from <process-name>
send     <message> to   <mailbox>
wait for <message> from <mailbox>
```

Asymmetrical addressing:

```
send     <message> to …
wait for <message>
```

☞ Client-server paradigm

Message-based synchronization

Addressing (name space)

Communication medium:

Connections	Functionality
one-to-one	buffer, queue, synchronization
one-to-many	multicast
one-to-all	broadcast
many-to-one	local server, synchronization
all-to-one	general server, synchronization
many-to-many	general network- or bus-system

Message-based synchronization

Message structure

- Machine dependent representations need to be taken care of in a distributed environment.
- Communication system is often outside the typed language environment.

  Most communication systems are handling streams (packets) of a basic element type only.

☞ *Conversion routines* for data-structures other then the basic element type are supplied …

… manually (POSIX, C)

… semi-automatic (CORBA)

… automatic (compiler-generated) and typed-persistent (Ada, CHILL, Occam2)

Message-based synchronization

Message structure (Ada)

```
package Ada.Streams is
   pragma Pure (Streams);
   type Root_Stream_Type is abstract tagged limited private;
   type Stream_Element is mod implementation-defined;
   type Stream_Element_Offset is range implementation-defined;
   subtype Stream_Element_Count is
      Stream_Element_Offset range 0..Stream_Element_Offset'Last;
   type Stream_Element_Array is
      array (Stream_Element_Offset range <>) of Stream_Element;
   procedure Read  (…) is abstract;
   procedure Write (…) is abstract;
private
   … -- not specified by the language
end Ada.Streams;
```

Message-based synchronization

Message structure (Ada)

Reading and writing values of any subtype S of a specific type T to a Stream:

```
procedure S'Write       (Stream : access Ada.Streams.Root_Stream_Type'Class;
                         Item   : in T);
procedure S'Class'Write (Stream : access Ada.Streams.Root_Stream_Type'Class;
                         Item   : in T'Class);
procedure S'Read        (Stream : access Ada.Streams.Root_Stream_Type'Class;
                         Item   : out T);
procedure S'Class'Read  (Stream : access Ada.Streams.Root_Stream_Type'Class;
                         Item   : out T'Class)
```

Reading and writing values, bounds and discriminants
of any subtype S of a specific type T to a Stream:

```
procedure S'Output      (Stream : access Ada.Streams.Root_Stream_Type'Class;
                         Item   : in T);
function  S'Input (Stream : access Ada.Streams.Root_Stream_Type'Class) return T;
```

Message-based synchronization

Message-passing systems examples:

POSIX:	“**message queues**”: ☞ ordered indirect [asymmetrical | symmetrical] asynchronous byte-level many-to-many message passing
MPI:	“**message passing**”: ☞ ordered [direct | indirect] [asymmetrical | symmetrical] asynchronous memory-block-level [one-to-one | one-to-many | many-to-one | many-to-many] message passing
CHILL:	“**buffers**”, ”**signals**”: ☞ ordered indirect [asymmetrical | symmetrical] [synchronous | asynchronous] typed [many-to-many | many-to-one] message passing
Occam2:	“**channels**”: ☞ ordered indirect symmetrical synchronous fully-typed one-to-one message passing
Ada:	“**(extended) rendezvous**”: ☞ ordered direct asymmetrical [synchronous | asynchronous] fully-typed many-to-one remote invocation
Java:	☞ no message passing system defined

Communication & Synchronization

Message-based synchronization

Message-passing systems examples:

	ordered	symmetrical	asymmetrical	synchronous	asynchronous	direct	indirect	contents	one-to-one	many-to-one	many-to-many	method
POSIX:	✔	✔	✔		✔		✔	byte-stream			✔	message queues
MPI:	✔	✔	✔	✔	✔	✔	✔	memory-blocks	✔	✔	✔	message passing
CHILL:	✔	✔	✔	✔	✔		✔	basic types		✔	✔	message passing
Occam2:	✔	✔		✔			✔	fully typed	✔			message passing
Ada:	✔		✔	✔	✔	✔		fully typed		✔		remote invocation
Go:	✔	✔		✔	✔	✔		fully typed	✔			channels
Erlang:	✔	✔			✔	✔		fully typed	✔			message passing

Java: ☞ no message passing system defined

Message-based synchronization in Occam2

Communication is ensured by means of a ‘channel’, which:

- can be used by one writer and one reader process only
- and is synchronous:

```
CHAN OF INT SensorChannel:
PAR
   INT reading:
   SEQ i = 0 FOR 1000
      SEQ
         -- generate reading
         SensorChannel ! reading
   INT data:
   SEQ i = 0 FOR 1000
      SEQ
         SensorChannel ? data
         -- employ data
```

concurrent entities are synchronized at these points

Message-based synchronization in Occam2

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```
CHAN OF INT SensorChannel:
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   SEQ i = 0 FOR 1000
      SEQ
         SensorChannel ? data
         -- employ data
```

Essential Occam2 keywords

```
ALT PAR SEQ PRI
ANY CHAN OF
DATA TYPE RECORD OFFSETOF PACKED
BOOL BYTE INT REAL
CASE IF ELSE FOR FROM WHILE
FUNCTION RESULT PROC IS
PROCESSOR PROTOCOL TIMER
SKIP STOP VALOF
```

☞ *Concurrent, distributed, real-time programming language!*

Message-based synchronization in CHILL

CHILL is the 'CCITT High Level Language',

where **CCITT** is the Comité Consultatif International Télégraphique et Téléphonique.

The CHILL language development was started in 1973 and standardized in 1979.

☞ strong support for concurrency, synchronization, and communication (monitors, buffered message passing, synchronous channels)

```
dcl SensorBuffer buffer (32) int;

…                                          receive case
send SensorBuffer (reading);                  (SensorBuffer in data) : …
                                           esac;

signal SensorChannel = (int) to consumertype;
…
send SensorChannel (reading)               receive case
   to consumer                                (SensorChannel in data): …
                                           esac;
```

Message-based synchronization in CHILL

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The CHILL language development was started in 1973 and standardized in 1979.

☞ strong support for concurrency, synchronization, and communication (monitors, buffered message passing, synchronous channels)

```
dcl SensorBuffer buffer (32) int;

…                                                receive case
send SensorBuffer (reading)  asynchronous  ──>   (SensorBuffer in data) : …
                                                 esac;

signal SensorChannel = (int) to consumertype;
…
send SensorChannel (reading)                     receive case
   to consumer         ──  synchronous  ──>      (SensorChannel in data): …
                                                 esac;
```

Message-based synchronization in Ada

Ada supports remote invocations ((extended) rendezvous) in form of:

- entry points in tasks
- full set of parameter profiles supported

If the local and the remote task are on *different architectures,*
or if an *intermediate communication system* is employed then:
☞ parameters incl. bounds and discriminants are ‘tunnelled’ through byte-stream-formats.

Synchronization:

- Both tasks are synchronized at the beginning of the remote invocation (☞ ‘**rendezvous**’)
- The calling task if blocked until the remote routine is completed (☞ ‘**extended rendezvous**’)

Message-based synchronization

Message-based synchronization in Ada

(Rendezvous)

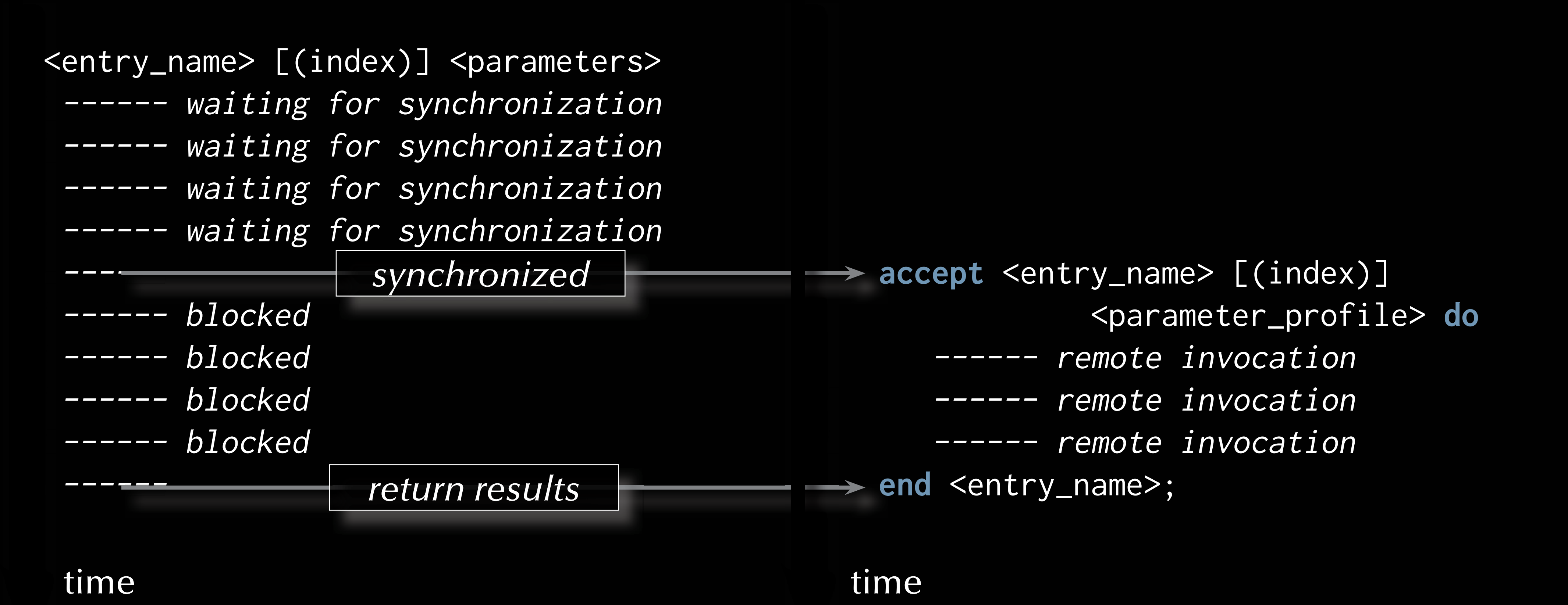
```
<entry_name> [(index)] <parameters>
 ------ waiting for synchronization
 ------ waiting for synchronization
 ------ waiting for synchronization
 ------ waiting for synchronization
 ---- synchronized ---->   accept <entry_name> [(index)]
                                  <parameter_profile>;
```

time

time

Message-based synchronization in Ada

(Extended rendezvous)

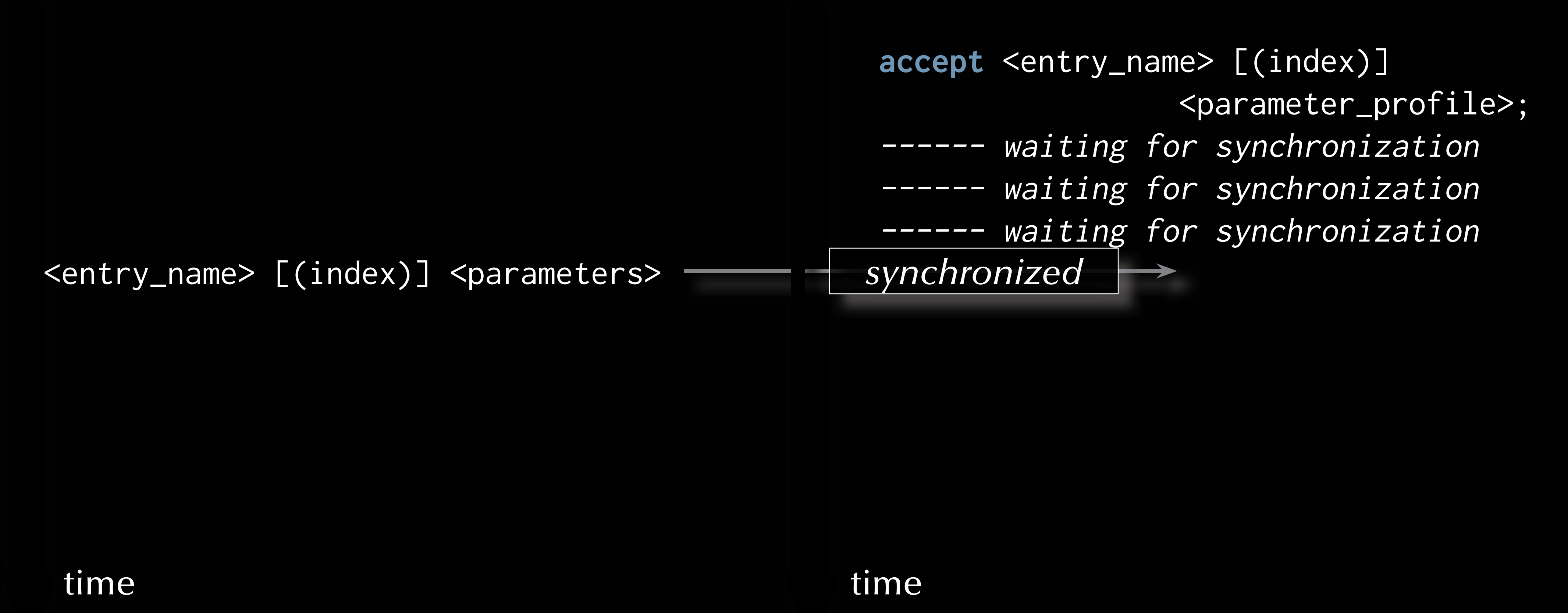


```
<entry_name> [(index)] <parameters>
 ------ waiting for synchronization
 ------ waiting for synchronization
 ------ waiting for synchronization
 ------ waiting for synchronization
 ---
 ------ blocked
 ------ blocked
 ------ blocked
 ------ blocked
 ------
```

```
accept <entry_name> [(index)]
            <parameter_profile> do
   ------ remote invocation
   ------ remote invocation
   ------ remote invocation
end <entry_name>;
```

Message-based synchronization in Ada

(Rendezvous)



```
accept <entry_name> [(index)]
                <parameter_profile>;
------ waiting for synchronization
------ waiting for synchronization
------ waiting for synchronization
```

```
<entry_name> [(index)] <parameters>
```

Message-based synchronization

Message-based synchronization in Ada

(Extended rendezvous)

```
                                                accept <entry_name> [(index)]
                                                               <parameter_profile>;
                                                ------ waiting for synchronization
                                                ------ waiting for synchronization
                                                ------ waiting for synchronization
<entry_name> [(index)] <parameters> ------------  synchronized  ---->
 ------ blocked                                    ------ remote invocation
 ------ blocked                                    ------ remote invocation
 ------ blocked                                    ------ remote invocation
 ------ blocked                                    ------ remote invocation
 ------ ------------ return results ------------> end <entry_name>;

 time                                           time
```

Message-based synchronization in Ada

Some things to consider for task-entries:

- In contrast to protected-object-entries, task-entry bodies *can* call other blocking operations.
- Accept statements can be *nested* (but need to be different).

  ☞ helpful e.g. to synchronize more than two tasks.
- Accept statements can have a dedicated *exception handler* (like any other code-block).

  Exceptions, which are not handled during the rendezvous phase are propagated to *all* involved tasks.
- Parameters cannot be direct 'access' parameters, but can be access-types.
- 'count on task-entries is defined,
  but is only accessible from inside the tasks which owns the entry.
- **Entry families** (arrays of entries) are supported.
- **Private entries** (accessible for internal tasks) are supported.

Summary

Communication & Synchronization

- **Shared memory based synchronization**
  - Flags, condition variables, semaphores,
    conditional critical regions, monitors, protected objects.
  - Guard evaluation times, nested monitor calls, deadlocks,
    simultaneous reading, queue management.
  - Synchronization and object orientation, blocking operations and re-queuing.
- **Message based synchronization**
  - Synchronization models
  - Addressing modes
  - Message structures
  - Examples